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**STUDY OF THE UPPER OCEAN STRATIFICATION THAT
CONTROLS PROPAGATION OF INTERNAL TIDAL
BORES IN COASTAL AREAS**

by

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June 2012

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**STUDY OF THE UPPER OCEAN STRATIFICATION THAT CONTROLS
PROPAGATION OF INTERNAL TIDAL BORES IN COASTAL AREAS**

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ABSTRACT

Coastal ocean stratification and optical properties have been analyzed over a month period from Moss Landing to Monterey Bay in Monterey, CA during October 2011. This research utilized measurements from four different observing systems: the Tethys long-range propeller-driven AUV, a Spray glider AUV, a SeaHorse moored profiler, and a thermistor chain to evaluate changes in conductivity, pressure, temperature, salinity, and optics over a four week time period. Each instrument observed the ocean structure and propagation of internal tidal bores in coastal areas, capturing the strength of the internal tides and their impact on the bed as they shoal and entrain sediment into the upper water column.

The main focus of this field study is to identify oceanographic processes responsible for heightened bed stress and the suspension of benthic material on the continental shelf. The primary objectives of this experiment are to (1) determine stratification conditions that are conducive for the generation of internal tidal bores in Monterey Bay, (2) track the presence of enhanced near bed sediment concentration and determine the site of maximum suspension, and (3) identify the generation areas of intermediate nepheloid layers. The combination of moored and mobile instruments provides spatial and temporal views of the resuspension of seabed materials and resolves the processes that control the formation of nepheloid layers over the Monterey Bay shelf.

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LIST OF ACRONYMS AND ABBREVIATIONS

AUV	Autonomous Underwater Vehicle
ISW	Internal Solitary Waves
MISO	Monterey Inner Shelf Observatory
ITB	Internal Tidal Bores
MBARI	Monterey Bay Aquarium Research Institute
IPB	Intelligence Preparation of Battlespace
ASW	Anti surface Warfare
INL	Intermediate Nepheloid Layers
SDV	Seal Delivery Vehicles
NLIW	Non Linear Internal Waves
CTD	Conductivity Temperature Depth
YD	Yearday

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I. INTRODUCTION

Monterey Bay is populated by non-linear propagating internal solitary waves (ISWs), a common feature of the coastal ocean. ISWs are generated by the conversion of barotropic tidal energy to baroclinic tidal energy at the shelf break and are characterized by abrupt changes in water column temperature followed by rapid oscillations (Cazenave et al 2011). ISWs are typically observed as sharp depressions of a near surface pycnocline that have a surface manifestation of bands of slicks and rough water propagating shoreward (Klymak 2003, Kropfli et al. 1999). When an ISW propagates onshore into shallower water, its interaction with a sloping topography, increased shear, and slowing speed due to the shoaling seabed causes the wave to steepen, increasing nonlinearity as water depth decreases (Tethys 2009). This steepening leads to increased instability until the internal wave eventually breaks and dissipates its energy through the generation of turbulent energy. Under strong stratification conditions, the leading edge can steepen and generate bore-like shockwaves which form a series of depressions in the water column ahead of the internal tidal bore (ITB), commonly referred to as an internal tidal soliton (Noble et al. 2009). The shoreward propagation of the ITB and solitons generates patches of energetic turbulence, mixing, and sediment resuspension (Boegman and Ivey 2008). The bore initiates sediment motion through Reynolds stress acting on the sea floor. This stress initiates sediment motion and then vertically entrains the sediment through positive Reynolds stress from a strong vertical component of wave velocity (Boegman and Ivey 2008). Material suspended in the water column may be transported onshore by partially rectified motions of these nonlinear waves of elevation and internal tidal bores (Noble et al. 2009).

Previous ITB laboratory, field, and numerical studies, analyze the generation mechanism for internal tidal bores both offshore and onshore, and their capability to suspend material on to the shelf after breaking on a sloping topography. Hosegood et al's 1999 field experiments along the south-east slope of the Faeroe-Shetland Channel provided high resolution data from moored instruments that determined an increase of suspended sediment in the water column is directly correlated to the presence of an ITB.

Boegman and Ivey's (2008) small scale laboratory representation of ISWs expanded upon Hosegood et al's research, and determined the necessary topographic slope to achieve the maximum suspended material in the water column. Venayagamoorthy and Fringer's (2006) high resolution numerical simulations agree with both Boegman and Ivey's and Hosegood et al's findings, and determined that the interaction of non-linear internal waves with the shelf break at critical angles results in the formation of an upslope surging ITB responsible for the transport of sediment onshore.

The results of Boegman and Ivey's, Venayagamoorthy and Fringer's, and Hosegood et al's experiments are comparable to Noble's (2001) field observations in San Pedro Bay CA, which specifically focuses on the cross-shelf transport due to shoaling internal tides. Noble's research concludes that in order for the transport of material to occur, strong internal tides must be present at the shelf where a strong down-slope flow occurs in both the mid-shelf mode and nearshore mode, resulting in enhanced mean flow field (Noble et al 2009). This flow field causes isotherms to tilt up towards the coast allowing tidal currents to carry sub-thermocline waters in to the surf zone.

The objective of this research is to identify stratification conditions that are conducive for the generation of internal tidal bores, and to track enhanced near bed sediment concentration to determine the location of maximum suspension on the continental shelf. The combination of moored and mobile instruments used during the experiment allows for both spatial and temporal views of near bed sediment suspension and the advection of nepheloid layers off Monterey Bay's shelf.

A. BACKGROUND

1. Coastal Ocean

Monterey Bay is located off the Central California coast from 121 ° W- 123° W longitude and 35° -37 ° N latitude. The underwater topography of Monterey Bay contains canyons and ridges that incise the continental shelf (Talley 2011). The Monterey Canyon is a classic example of a submarine canyon, and is an active test site for determining a canyon's effects on the generation of internal tides (Petruncio 1998). The southern edge of the Monterey Canyon is characterized by a steep shelf break with depths

ranging from 100 m to 1000 m over a 5000 m distance (Tjoa 2003). The shelf is frequented by energetic non-linear internal waves and is typically a coastal upwelling environment from spring until summer (Cazenave et al. 2011). These steep shelf breaks are potential generation sites for ITBs and are the focus of the 2011 Monterey Bay internal nepheloid layer generation research.

a. Winds

Wind drives the surface circulation of the ocean and plays a large role in mixing the surface layer and causing upwelling or downwelling conditions (Tjoa 2003). During the spring and summer months, maximum equatorward wind stress occurs off northern California, propelling periods of strong seasonal upwelling along the California coast (Hickey 1998). Winds from the north transport cold, fresh water, while winds from the south transport saline water (Tjoa 2003). Wind forcing propels coastal upwelling, and the advection of water into and out of the Monterey Bay, and in turn impacts the stratification in the region (Rosenfeld 1994). Previous research (Collins 2002) demonstrates that the surface waters in Monterey Bay during the spring and summer upwelling periods are much colder than those recorded during periods of downwelling (Tjoa 2003).

b. Stratification

Stratification in California coastal areas are controlled by large-scale advection and upwelling of water masses (Hickey 1998). In Monterey Bay, the stratification during the summer is much stronger than during the winter months. During the summer months Tjoa (2003) identified ocean characteristics of a strong, near surface stratification, with strong near-surface thermal gradients nearly reaching the surface, and a strongly stratified water column approximating a two-layer system. During the winter months the surface stratification almost completely disappears and is located much deeper in the water column due to an increase in surface stress from environmental conditions.

c. Internal Waves

Internal waves occur at the interface between different density layers within the ocean (Batteen 2012). Scientists have developed several different theories to describe internal waves: rigid-lid assumption, continuously stratified, and bounded ocean. Previous non-linear internal wave studies focus specifically on two-layer stratification models to demonstrate the ability of internal waves to change at water density interfaces. As the waves propagate horizontally along the sharp density interface, such as at a shelf break, instability and localized mixing are observed (Boegman and Ivey 2008). Internal waves typically have wavelengths between 100 m and 100 km with phase speeds between 0.1 ms^{-2} and 2 ms^{-2} , and a frequency that is limited by buoyancy frequency, N (Batteen 2012). The results of Boegman and Ivey's 2008 experiment draw connections between nonlinear internal waves and sediment suspension. The experiment demonstrated how internal waves cause sediment erosion at the seafloor resulting in substantial mixing and suspension of material in the water column.

2. Internal Tides in Coastal Ocean

a. Generation

Nonlinear internal tides are often observed over continental shelves and shelf breaks. They are characterized by oceanographic features such as solitary waveforms and high amplitude displacement (Cazenave et al. 1998). Typical internal tides that propagate over the continental shelf have current speeds between $5\text{--}20 \text{ cms}^{-1}$ and isopycnal displacement amplitudes between $20\text{--}50 \text{ m}$ (Cazenave et al. 1998). When an internal tide propagates onshore it can dissipate its energy through nonlinear steepening and the generation of turbulence. The steepening process leads to the creation of internal waves with higher frequency that propagates along the shelf with a wave period on the order of $20\text{--}30$ minutes (Noble et al. 2009). Extensive research on the Monterey Bay shelf provides evidence that NLIW populate the Monterey Bay shelf break (Cazenave et al. 1998). Internal wave generation over the continental slope is most efficient when the bottom slope is critical for the particular wave frequency (Petruncio 1998). When the bathymetric slope is equal to the slope of the energy flux vector, the

energy density goes to infinity and the group velocity disappears. In this situation researchers believe that strong bottom intensification of the baroclinic currents and an unstable turbulent bottom boundary layer occurs (Wunsch 1968). In this scenario the plane of forcing motion and plane of particle motion generate strong internal tides (Petruncio 1998). The most common location for internal tides are at the shelf break where the oceanographic topography changes from supercritical on the continental slope, to subcritical at the continental shelf, over a relatively small distance (Petruncio 1998).

Changes in stratification alter the internal wave's interaction with the sea bed, changing the location for the generation site of INL and benthic particulate transport. The saw tooth trajectories of the instruments used during this experiment aimed to capture several possible cross shore generation sites of INL at numerous depths. Through temporally and spatially tracking the propagation and advection of benthic material cross shore, we can better assess the generation site of INL which previous experiments failed to achieve.

b. Nonlinear Propagation

(1) Internal Tidal Bores. As an internal wave propagates shoreward its non-linearity increases with decreasing depth and upon interaction with the shelf break or a sharp change in topography, the leading wave of depression causes a drawdown of the density interface with the upslope lower layer fluid passing underneath the wave trough (Boegman and Ivey 2008). A separation bubble between the adverse pressure gradient and the shoaling wave is created due to the upslope jet flow, causing the downslope flow to separate forming an internal bolus (Boegman and Ivey 2008). The internal tide dissipates its energy through generating the internal tidal bore (Noble et al 2009).

Regional topography and stratification in the water column control an internal tidal bores ability to transport material onshore (Noble et al. 2009). Resuspension is directly attributed to near bed viscous stress and to near bed patches of elevated positive Reynolds stress generated by the vertical structures. When the internal wave encounters a region where the wave amplitude is similar to the depth of the layer of

fluid below the thermocline, the surface layer has comparable thickness to the layer below the thermocline, or the thermocline intersects the bed, the properties of nonlinearity and asymmetry of currents are enhanced (Noble et al. 2009). In these situations sediments suspended in the water are carried upslope through the nonlinear transport of ITB (Noble et al. 2009).

(2) Solitons. Solitons are commonly observed in coastal regions where the water column is stratified. Solitons characteristically have short periods, are strongly nonlinear, create steep disturbance in the water column, and are typically observed on the leading edge of an ITB (Tjoa 2003). They are readily identifiable by the vertical alignment of current and isotherm displacements (Liu 1988). In coastal regions where a strong stratification is present, vertical displacements of a soliton are observed to be 2–4 times greater than the pycnocline depth (Tjoa 2003).

The leading edge of an ITB steepens due to nonlinear effects which causes the formation of large amplitude solitons, with displacements up to 5 times the upper layer depth in strong stratification conditions observed off Northern Oregon (Stanton and Ostrovsky, 1998). The observation site during this experiment in Monterey Bay is also inshore of a shelf break, but with weaker stratification. Both regions have a distinct shelf break located offshore of the site of solitary internal wave observations (Tjoa 2003).

c. Sea Floor Interaction

Klymak et al (2003) finds large amounts of optical backscatter near the bottom due to the resuspension of sediment and particles over the Oregon continental shelf. These observations suggest that at the seabed there is heightened bed stress, as a result of an increase in near-bed velocity and friction. The two likely sources for the turbulence found in the 2011 Monterey Bay experiment are attributed to shear instability and bed stress driven turbulence as found in Klymak et al's experimental results. Benthic material is suspended into the water column when the seabed experiences erosion from strong turbulent shear stress caused by nonlinear internal waves and low-frequency currents.

3. Internal Nepheloid Layers

Internal nepheloid layers are mid-depth layers of suspended material that are thought to form on sloping sea floors and advect into regions of deep water from continental shelves and slopes (McPhee-Shaw 2002). INLs may form by the interaction of internal waves with a sloping boundary, leading to increased levels of shear, strain, and turbulent mixing. The increased stress on the bottom boundary erodes sediment from the bed and leads to the suspension of material within the water column. Previous INL research (McPhee-Shaw 2002) focuses on the horizontal intrusions generated by boundary layer turbulence. MCPhee-Shaw determined that intrusions typically formed in regions where the incident and reflected wave beams overlap on the slope. Previously the formation of INLs were thought to coincide with the critical reflection of semidiurnal internal tides, however MCPhee-Shaw's 2002 laboratory experiment found that intrusions are most intense at supercritical sloping conditions, where the incident wave is slightly steeper than the topographical slope. Experiments specifically conducted on the Monterey Bay Shelf (MCPhee-Shaw 2002 and Cazenave et al. 2011) note that intrusions can extend 10–20 km offshore propagating at a maximum rate of 1 km per 3.5 hours.

B. STUDY OBJECTIVES

The 2011 Monterey Bay experiment was part of a larger National Science Foundation project, including scientific research teams from Moss Landing Marine Laboratory, MBARI, and Naval Post Graduate School. The main focus of the NSF project is on benthic exchange over the continental shelf. Prior to the Monterey Bay 2011 experiment, there was no direct study testing the correlation between mixing and boundary intrusion dispersal on the continental shelf. The conclusions drawn from the 2011 experiment can easily be translated to deeper continental margins due to the similarities between Monterey Bay and other classic examples of coastal regions.

The overarching object of this field study is to identify the oceanographic processes responsible for heightened bed stress and turbulent mixing that causes the suspension of bottom particulates in the water column and across the continental shelf. The three main objectives for this field experiment are to (1) determine the stratification

conditions across Monterey Bay that are conducive for the generation of internal tidal bores (2) temporally and spatially track the occurrence of enhanced near bed sediment concentration and determine the location of maximum resuspension (3) identify intermediate nepheloid layers in the water column transported by intrusions cross-shelf and improve our understanding of formation characteristics

1. Oceanographic Motivation

Upwelling regions along the coast are essential to maintaining ocean productivity due to the injection of nutrients, such as benthic iron in the upper water column. Turbulent mixing and boundary-interior exchange play crucial roles in sustaining ecosystems by supporting these biogeochemical cycles through the export of material from the continental shelf seabed. This near-bed mixing can also lead to significant problems like algal blooms.

a. Coastal Biological Productivity

Upwelling coasts are known for their productivity in phytoplankton growth due to the movement of nutrient rich benthic material into the interior of the water column (Johnson et al. 1999). In order for nutrients to enter the water column a constant supply of upwelled water must be present. The Monterey Bay region is an area of high biochemical productivity while those areas extending south suffer from low productivity despite large amounts of nutrient rich water. One possible explanation for Monterey's high productivity is attributed to the width of its shelf. The large shelf width is capable of maintaining a mud belt that traps nutrients and heightens phytoplankton productivity, while southern shelves are too narrow to store the required nutrients for large growth rates (Bruland et al. 2001). Applying this concept to a global context helps bring clarity to the relationship between nutrient rich waters and shelf width in coastal upwelling areas.

b. Algae Blooms

Harmful algae bloom species, such as *Lingulodinium polyedrum*, have a cyst stage and may be the cause behind the generation of toxic blooms when they are

transported up into the water column through benthic-interior exchange (Rines et al. 2002 and McManus et al. 2007). Subsurface layers of algae bloom species were found in coastal waters on the west coast and suggest these events are due to benthic exchange found in the water column (Rines et al. 2002 and McManus et al. 2007). Tracking the evolution of benthic material may help explain the decoupling between upwelling and coastal blooms. Previous AUV experiments conducted in Monterey Bay (Ryan 2005) captured the connection between the presence of intrusions and biology over the outer shelf. The temporal evolution tracked material lifted off of the seafloor and transported vertically in the water column along tilted isopycnals towards the euphotic zone.

2. Naval Relevance

a. Oceanographic Application

The area of interest in the ocean can range from large scale investigations to small scale highly detailed surveys of environmental characteristics such as tides, waves, currents, acoustic propagation, and winds. It is essential to gather oceanographic data before conducting naval operations in order to provide information on currents, internal waves, and bottom geophysical parameters, to deem an area safe to carry out a mission (Dept of Navy 2004). This oceanographic knowledge can ensure safe and proficient implementation of naval objectives, and can drastically alter the outcome of a mission.

The ever increasing enemy submarine threat makes the establishment of an effective Anti-Surface Warfare (ASW) paramount in the US Navy. A submarine's first line of defense relies heavily on acoustics, which gathers information through target detection, tracking, and identification. The presence of a nepheloid layer in the surrounding waters of a submarine can significantly limit the ability to achieve this line of defense, due to the heightened backscatter present in the water. A better understanding of the spatial and temporal evolution of entrained material coupled with the propagating ITB will improve a submarine's ability to operate effectively while encountering these ocean processes over or a near continental shelf.

ITBs and associated soliton wave packets can directly affect special operations such as amphibious landings and SEAL operations. Seal Delivery Vehicles (SDVs) are deployed from specially crafted chambers on a submarine to maximize the secrecy of the mission. The SDVs are designed to navigate in shallow waters for several miles to reach their intended target. The presence of an ITB in close proximity to the SDV adds difficulty to the intended course of transit, due to the vehicles inability to maintain control in the presence of large amplitude current and density fluctuations (Crabbe 2007). These conditions severely decrease the SDV's visibility due to large amounts of particulate in the water column, and could force the vehicle to surface, exposing itself in enemy territory. The resuspended material that often is associated with ITBs could also create decreased visibility for the SDV. Understanding where ITBs occur and their association with suspended sediment is important to maintaining the safety of the SEAL teams as well as maintaining covert and successful operations.

Understanding oceanographic processes is essential to Mine Countermeasures Missions (MCM) whose principle area of concern is near shore. In order for MCM to effectively combat mine threats in the ocean MCM is broken down in to four different categories: reconnaissance, clearance, sweep, and protection (Dept of Navy 2004). It is essential to gather oceanographic data before conducting naval operations in order to provide information on currents, internal waves, and bottom geophysical parameters to allocate an area as mineable. Endowed with this knowledge the MCM team can determine changes in mine-like contacts in the ocean, indicating if a mine has moved, if mine stockpiles have been accessed, or if mining operations have been undertaken. Understanding the fundamentals behind oceanographic processes allows the MCM team to act against possible mine threats prior to carrying out a mission.

b. Undersea Technology Advancements

When planning strategic and tactical naval operations it is essential to have a clear understanding of the area of interest (Dept of Navy). In the past, oceanographic data was collected by means of hull mounted or towed systems that required extensive ship support and faced limitations to depths reached based upon the

tow cables length. Through replacing towed arrays with AUVs, such as the NPS Spray glider and the MBARI Tethys, the hydrographic, optical, and acoustic data is obtained more readily in diverse environmental settings (Dept of Navy 2004). AUVs survey greater distances and depths than towed systems at significantly less cost, making the AUV extremely cost effective. Naval ships are now able to remain offshore, yet still acquire information about near-shore shallow waters through AUV implementation. The information gathered by AUVs is coupled with previous survey data and models to provide the Navy's Tactical Decision Aids with precise information of the undersea battlespace (Dept of Navy 2004). Through understanding the presence of internal tidal bores and their effect in the upper layers of the water column the Navy's tactical decision aids can better determine and assess the best possible scenario at sea for littoral operations.

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II. OBSERVATIONS AND DATA REDUCTION

A. PHYSICAL SETUP

1. Monterey Bay Shelf Field Site

The Monterey Bay shelf, located off the Central California coast, is an optimal location for the experimental study of the temporal and spatial evolution of internal tidal bores and nepheloid layers. A large concentration of mud is located in this area of Monterey Bay, and the wide shelf supports these “mud belt” deposits from winter storm runoffs from local rivers and streams. Monterey Bay’s steep continental shelf break is located on the outer edge of the experimental test site (Figure 3), providing a good site for internal tide generation. Like Monterey Bay, much of the U.S. west coast, south of the Columbia River, experiences winter storm swells and coastal upwelling (Eittreim, 2002) making the experimental site a good location for research. That is, the oceanographic processes identified in Monterey Bay can be extended to other areas of coastal upwelling.

B. INSTRUMENT SYSTEMS

This analysis utilizes data from two AUVs that mapped temperature, conductivity and optical backscatter in cross-shelf sections. The long-range AUVs provide temporal and spatial coverage of the water-column and offer detailed information on changes in stratification, and water column particulate load. A moored profiler and a thermistor chain were also deployed at 70 m depth throughout the experiment. These platforms continuously measure CTD, optics, and turbulence over a location of heightened sediment suspension activity. The combination of static and dynamic instruments provides a temporal and spatial depiction of internal ocean processes that generate and evolve within Monterey Bay, as well as the ability to track the resuspension of material as it moves on and off shore.

1. Long Range Autonomous Underwater Vehicle

A highly energy efficient propeller-driven AUV created to carry chemical and biological sensors over long ranges, Tethys is capable of making observations beyond the upwelling zone, allowing researchers a foundation for studying blooms during their month-long lifetime (MBARI 2012). Tethys's endurance and various operating modes enables the instrument to wait in low power configuration allowing a new generation of biological process experiments (MBARI 2012). Tethys operates at speeds of 0.5 m/s to a specified location and maintains satellite communications to shore-based scientists and GPS locations while it is at the surface. Tethys can only determine its position while it is at the surface, therefore the exact location of data collection received is not precisely known, but instead provides only a rough estimate. Strong internal tides, surface winds, and waves can affect Tethys ability to remain on course. Several times during the experiment, Tethys was pushed off of its intended course due to the presence of strong currents. Upon each surfacing, the instrument conducts a GPS check and alters its intended course to regain the proper track, if necessary.

The Tethys experiment took place in Monterey Bay from YD 285 to YD 291. The Tethys instrument flew with excellent position precision throughout the experiment, making tight consistent cross-shore transects in Monterey Bay from 121.85° W to 122.05° W at average latitude of 36.7208° N (Figure 1). The cross-shelf path chosen for Tethys ensured data collection on both the continental slope and continental shelf (Figure 3) to capture both the generation site of ocean processes, as well as the transport of benthic material off shore. Tethys maintained an average speed of 0.5 m/s throughout the experiment and measured to a maximum depth of 110m. An on-board altimeter and bottom avoidance system allowed Tethys to fly with a relatively low height index above the seabed providing high resolution sampling of seabed processes.

Tethys is equipped with a CTD (Conductivity Temperature Depth) sensor to determine ocean temperature and salinity. The temperature, salinity, and pressure data extracted from CTD readings provide regional descriptions of the oceanographic area of interest. Tethys's conductivity sensor did not function well during the experiment resulting in unsalvageable salinity data (Figure 4). Lacking this data introduced problems

for calculating potential density and buoyancy frequency in the water column. The temperature readings for Tethys were of high quality throughout the experiment, and because of the close relationship between salinity and temperature, the temperature data may be used to infer the water column density.

Tethys has three different optical sensors for detecting particulate density in the water column. The optical backscatter sensors operating at 650 nm and 450 nm are sensitive to enhanced particulate load near the seabed caused by the suspension of benthic material, while a fluorometer is sensitive to biological backscatter, detecting the presence of chlorophyll. The optical backscatter data are related to the concentration of particulate in the water column and thus provide a picture of the temporal and spatial evolution as sediment is entrained in the water column and advected offshore. No calibrations of sediment concentration to optical backscatter were performed for this analysis. For this study, the optical sensor sensitive to 650 nm is used because it captures the most significant density signature in the water column (Figure 5). These particulate proxy measurements are used to generate high resolution timeseries of the ocean and distinguish where and when a nepheloid layer formation over the continental shelf was present.

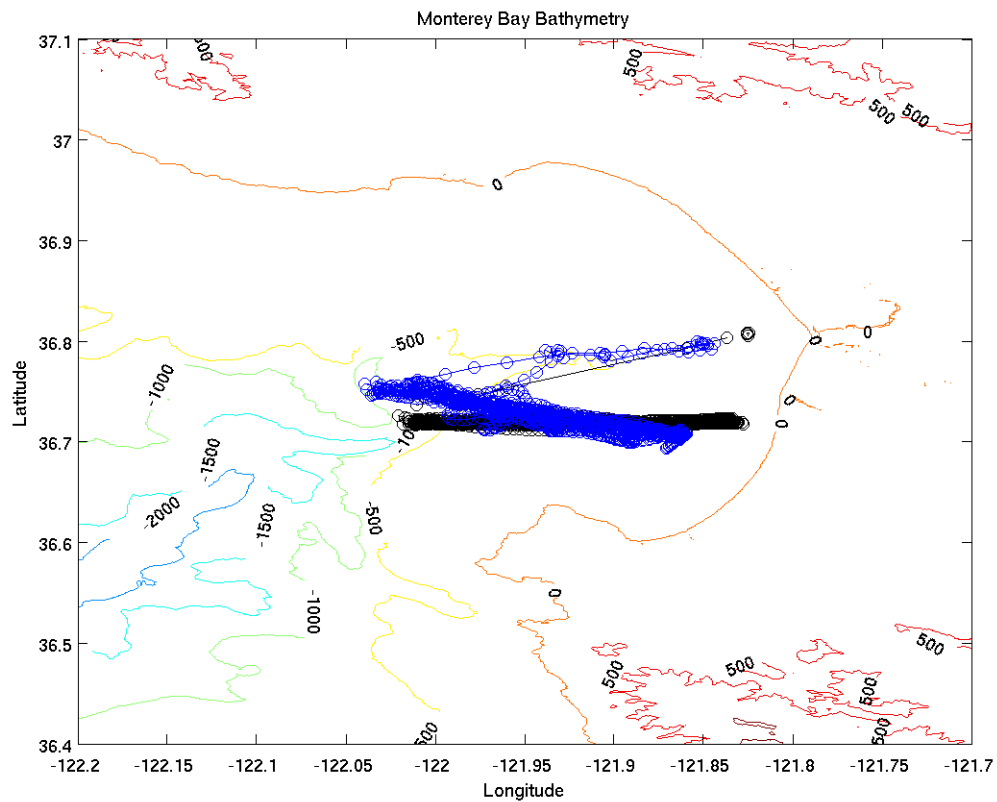


Figure 1. Bathymetric map of Monterey Bay provides a spatial view of the Spray glider and Tethys AUV transects across the Southern Monterey Bay Shelf. Spray glider transects denoted in blue and Tethys transects denoted in black. The average latitude that Tethys flew over the experiment was 36.7208° N. The average latitude the Spray Glider flew over the course of the experiment was 36.7286° N.

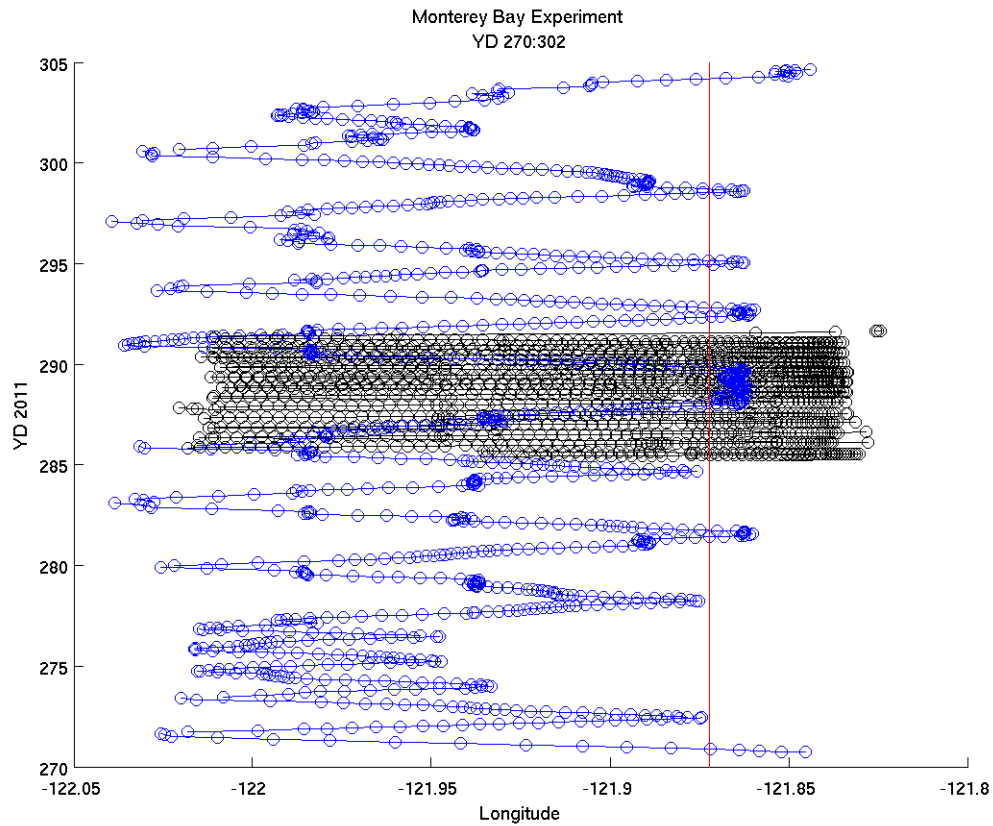


Figure 2. Longitude and temporal depiction of the AUVs and moored profiler data acquisition during the Monterey Bay experiment from YD 270 -302. The blue 'o' indicates Spray glider's cross shore transects, the black 'o' indicates Tethys's cross shore transects, and the red solid line indicates the location of the SeaHorse profiler and the T-Chain mooring.

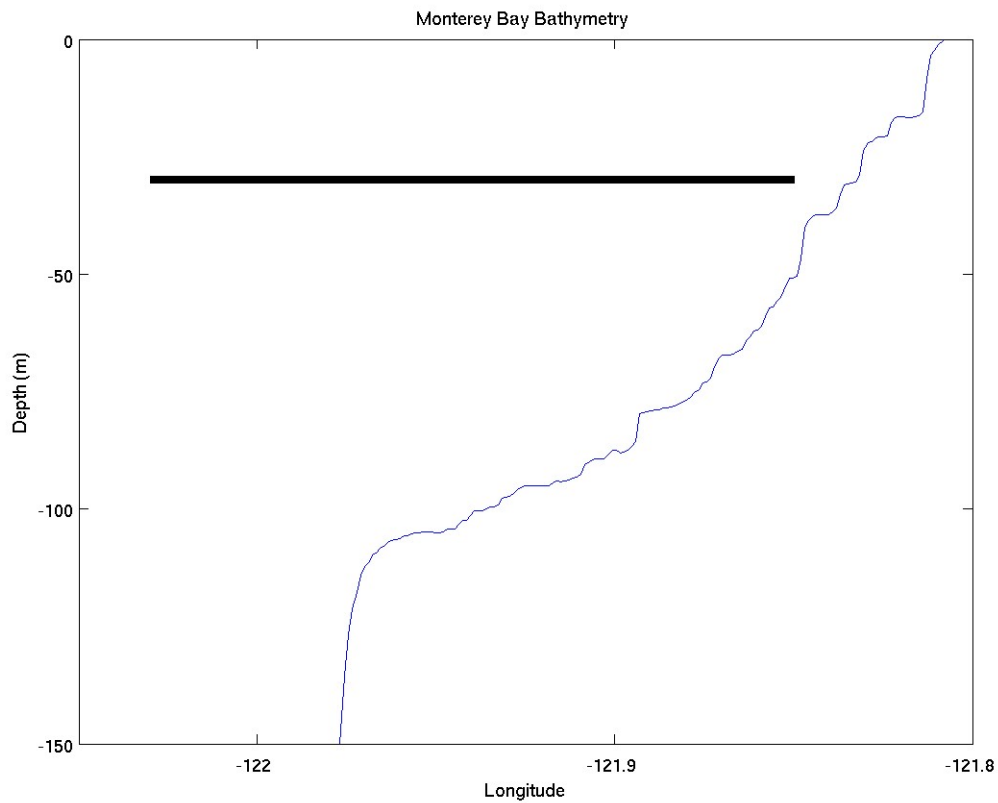


Figure 3. Monterey Bay bathymetry along the cross-shelf Tethys vehicle transects. The black line indicates the path of Tethys's cross-shore transects during the experiment. The AUV transects extend from near shore to the continental shelf break.

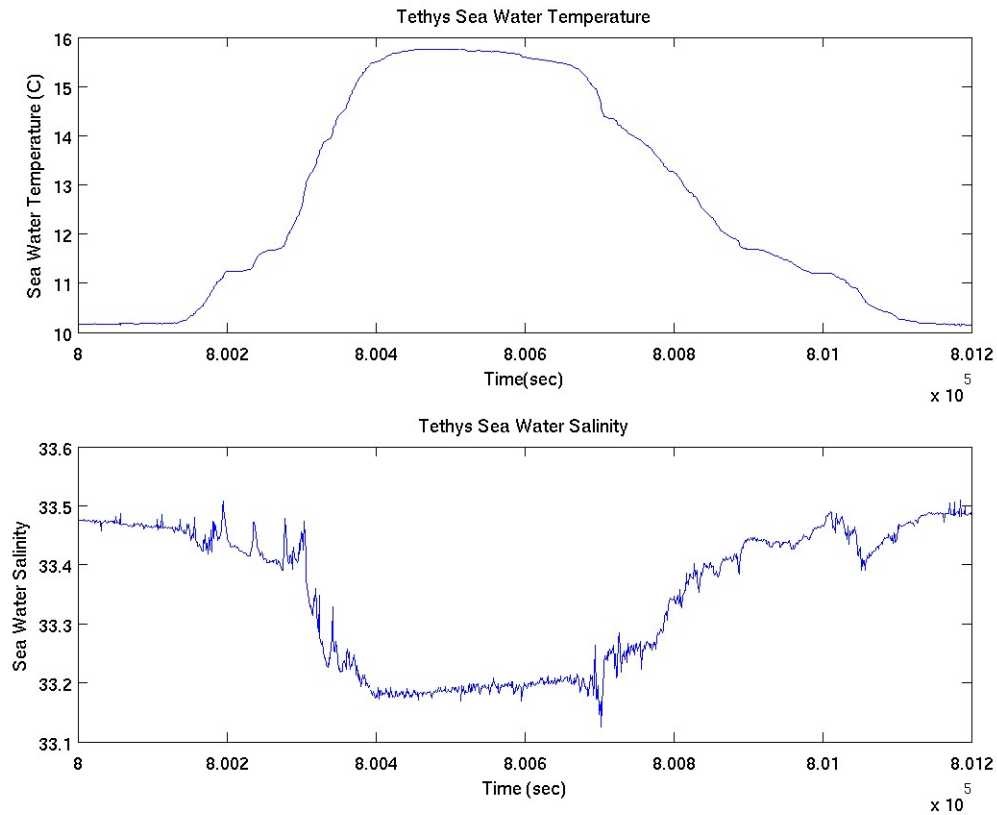


Figure 4. Temperature and salinity data taken from Tethys. The upper plot is extracted temperature and shows high-quality temperature data collected during the experiment. The second plot is extracted salinity data, and the spiked and highly variable measurements were not salvageable for stratification analysis.

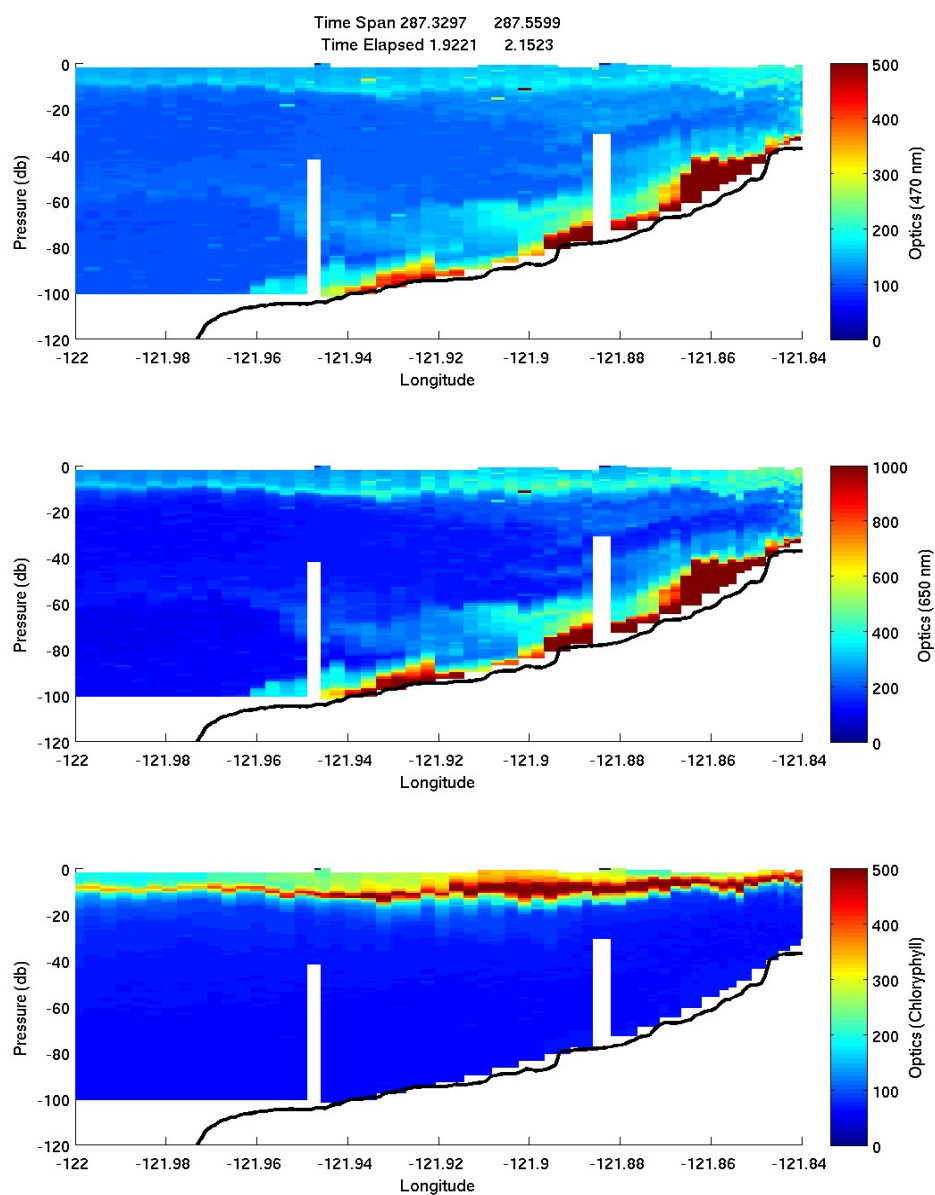


Figure 5. Tethys transect on YD 287.3297 showcasing the responses of the three optical sensors onboard the vehicle. The first graph is data collected by a sensor that is sensitive to particulate backscatter at 470 nm. The second graph is data collected by a sensor that is sensitive to particulate backscatter to 650 nm. The third graph is data collected by a Chlorophyll sensor, and therefore the optical signature is confined to shallow depths where phytoplankton are most abundant. The collected data from the sensor responsive to 650 nm is used to analyze particulates in the water column due to its heightened response in comparison to the 470 nm sensor.

2. Spray Glider

The Spray is an underwater glider that provides a small long-range autonomous platform for long-term ocean measurements, and was developed by a research group at Scripps under ONR sponsorship. The Spray glider can operate for months at a time and makes transects in a see-saw shape by using a hydraulic pumped buoyancy engine (www.spray.ucsd.edu). The Spray glider used in this experiment is owned and operated by the Naval Post Graduate School. Through changing its volume the Spray alternately glides upwards and downwards at angles of 18–25 degrees and speeds of 25–35 cm/s. Each wing of the Spray contains a combined GPS and Iridium antenna that ensures continued communication and navigation in the event that one wing becomes damaged. Figure 6 illustrates the motion of the Spray glider upon surfacing, receiving a fix, and re-submerging (Figure 6). Because of a lack of inertial navigation and bottom tracking, the Spray glider faced more severe navigation problems than the Tethys, and found itself surfacing at locations well off its desired course. Therefore, the Spray glider experienced more variability in its path towards its intended destination and did not sample the near-bottom water column well.

The Spray glider observation took place in Monterey Bay from YD 270 to YD 302. During the course of the experiment the Spray glider received target waypoints from a remote computer at Naval Post Graduate School to transect from Moss Landing to Monterey Bay. Once surfaced the Spray glider received one of three way points to travel to (036.83° N, 121.9° W, 036.76° N, 122.05° W, and 036.7° N, 122.4° W) depending on its location and intended destination. Due to environmental ocean processes, such as currents and tides, coupled with the inability for the Spray glider to check its actual course while submerged, the flight path of the Spray glider, was more variable when compared with the higher speed of Tethys AUV (Figure 2). An average latitude of 36.7286° N was determined for the Spray glider experiment (Figure 1). The Spray glider reached three target depths ranging from 58 meters to 288 meters during the experiment. As a precautionary method to account for any height anomalies in the seafloor, the Spray

glider always flew at least 12 meters above the seabed. The data set extracted from the deeper depths help provide a good view of the stratification conditions extending out from the continental shelf.

The Spray glider carries the same variety of sensors found on the Tethys instrument, but has a single standard optical backscatter sensor. The Spray glider is equipped with a Seapoint 650nm Optical Backscatter Sensor (OBS). The data captured by this instrument during the experiment highlights the flux of suspended particulate in the water column during periods of high stress near the seabed. Due to the extended period of time the Spray glider remained underwater the sensors began to experience problems beginning on YD 292 remaining until the culmination of the experiment. The optical resolutions recorded completely saturated data as a result of diminished sensitivity of the LED light. This particular problem is difficult to avoid in an experiment of this duration, simply due to bio-organisms attaching to the instrument.

Unlike the Tethys instrument, the Spray glider only recorded data while surfacing and therefore acquired only half as much data as Tethys during its short deployment, significantly limiting the resolution of each transect. The poor resolution of each transect coupled with Spray's inability to acquire data of suspended material near the seabed, requires the main focus of near-bed density signature to be confined to the higher spatial resolution data set acquired from the Tethys AUV.

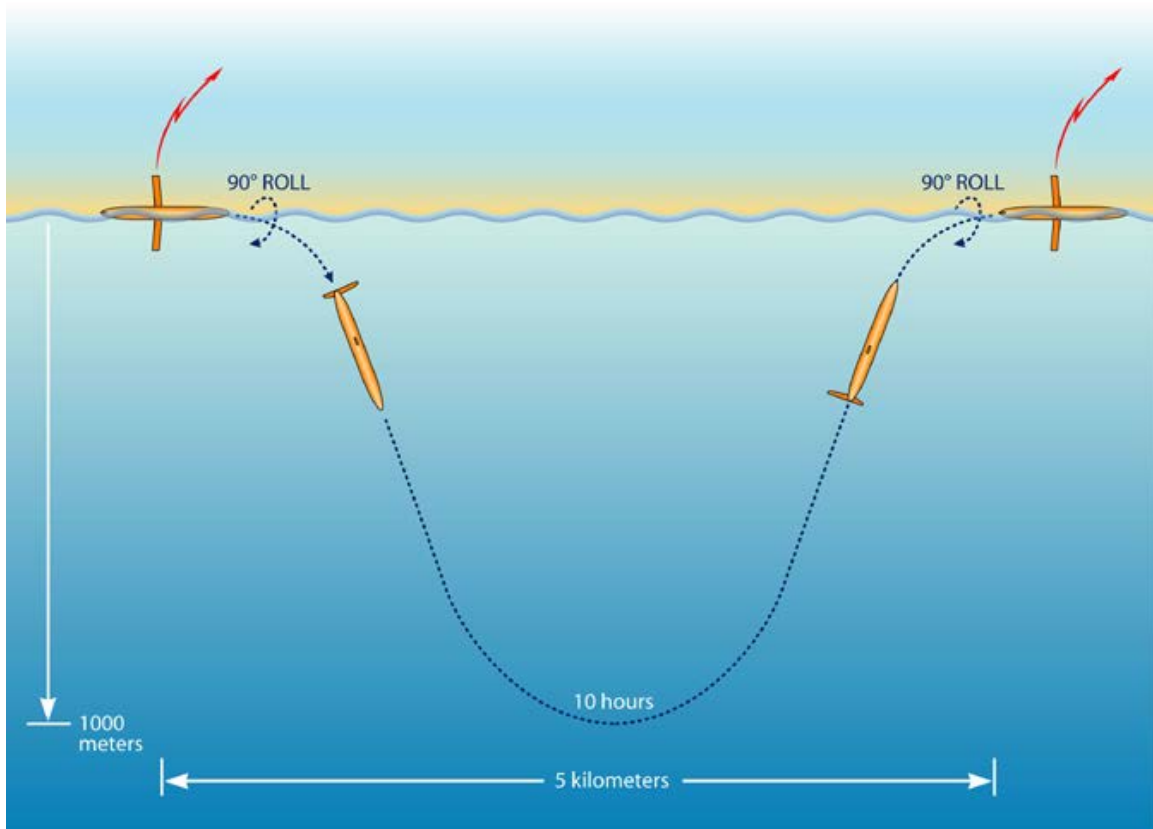


Figure 6. (From Scripps) Illustration of the Spray glider's movements. The Spray glider starts at the surface to receive GPS communication from a remote site which establishes an intended destination and depth to travel. Once received, the Spray glider dives to the established depth and then surfaces to receive a GPS signal to ensure it is still on track to arrive at the intended destination.

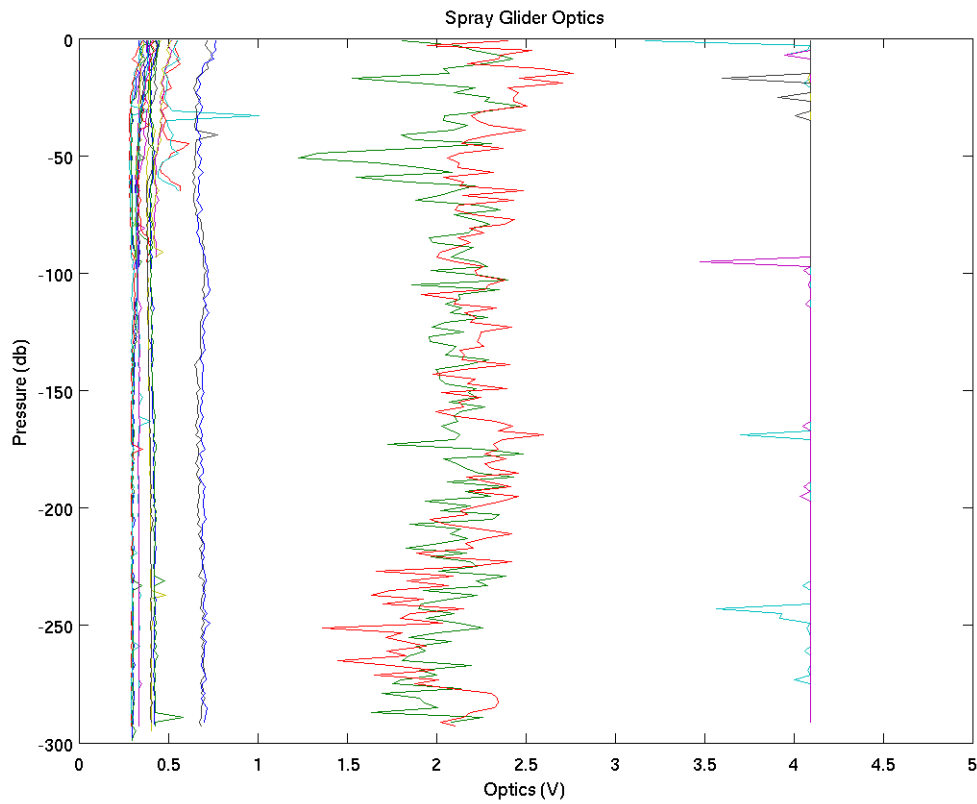


Figure 7. Optical backscatter data from the Spray glider. The saturation point for the optical backscatter is 4.096 V. The green and red profiles indicate readings on YD 289 when the Spray glider's optical sensor began experiencing a heightened fouling issue. On YD 292 the Spray glider's optical sensor reached saturation point and collected unusable data throughout the rest of the experiment as illustrated by the cyan and magenta curves on the right side of the plot.

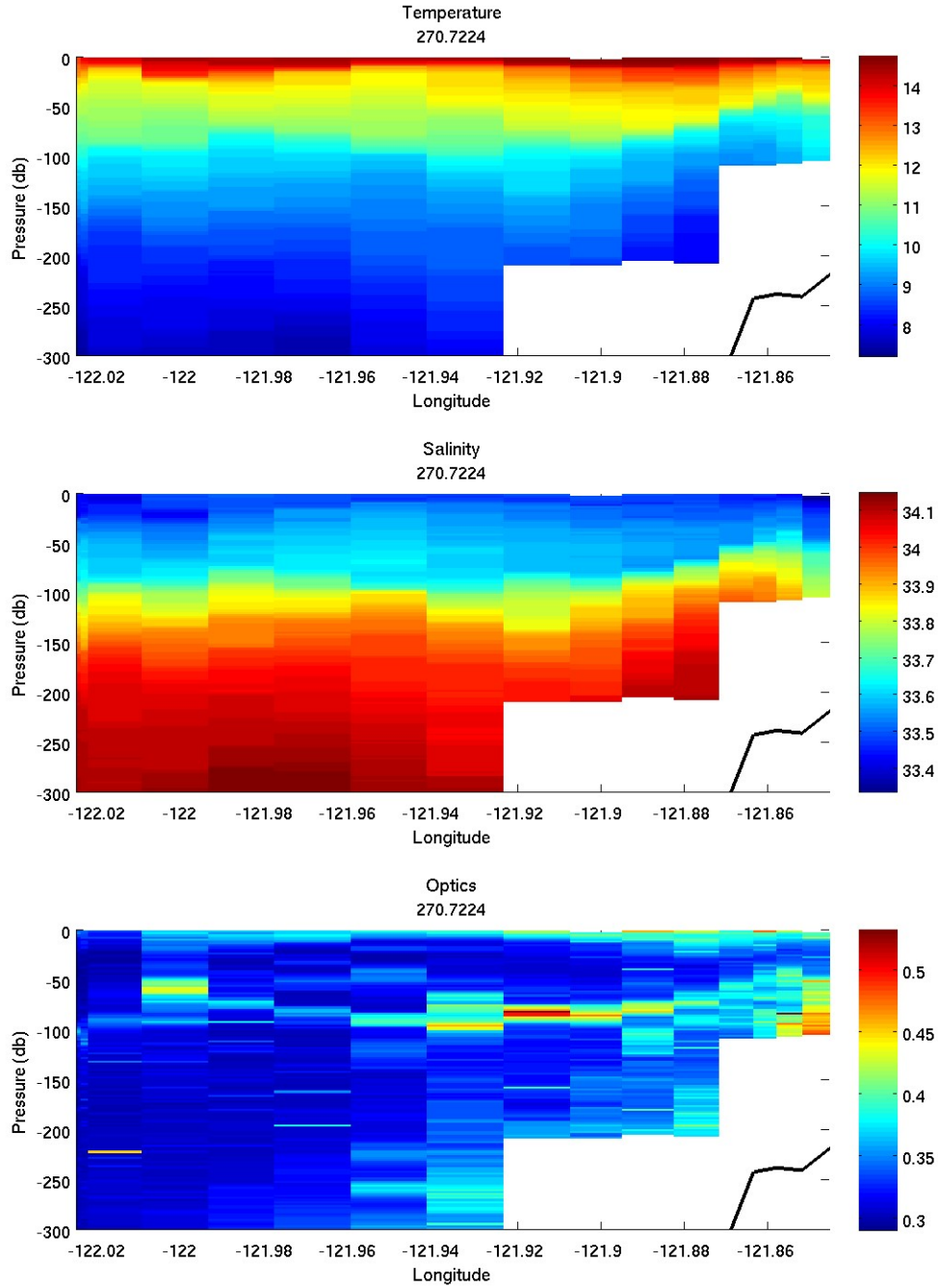


Figure 8. Spray glider transect on YD 270.7224. The top panel is a cross shelf temperature section. The black solid line denotes the seafloor depth. The middle panel is a cross shelf salinity section. The third plot is a cross shelf section of optical backscatter.

3. SeaHorse: Moored Profiler

The “SeaHorseTM” (ODIM Brooke Ocean) continuously profiling mooring system provides full water column profile data throughout the course of the Monterey Bay experiment. The SeaHorse system, operated by Moss Landing Marine Laboratory, is equipped with CTD sensors and optical sensors. The optical instruments on the SeaHorse provide a continuous one-month temporal description of nepheloid layers. The capabilities of this system allow us to capture intrusions regardless of what isopycnals they disperse along, or whether the depth of the isopycnals vary throughout the course of a day. During the course of the experiment the SeaHorse was deployed at 70 m depth on Monterey’s continental shelf in an effort to capture intrusions once they have detached from the boundary layer.

4. T-Chain

A taut-line mooring equipped with equally spaced SBE 39 temperature sensors ranging from 0 to 60 m depth. The T-chain is co located with the SeaHorse moored profiler extending to depths of 67.5 m along Monterey’s seabed. The T-Chain temperature data extracted over the course of the experiment provides high temporal resolution measurements of the water column at the 70 m depth on Monterey’s continental shelf.

D. DATA REDUCTION

At the conclusion of the field experiment, the data and information stored in the Spray glider, Tethys, SeaHorse, and T-Chain instruments were uploaded into Matlab where the raw data was extracted and sorted into profiles, sections, and bins, in order to generate temporal and spatial views of water column properties across the Monterey Bay shelf.

The raw data was sorted by determining when the AUV was diving, surfacing, or stationary. The sea water pressure extracted throughout the experiment indicated the AUV’s depth in the water column, and the low pass-filtered temporal derivative of pressure was used to determine whether the AUV ascending, descending, or stationary at

the surface. For each data record, the AUV status was determined, -1 indicating that the AUV is ascending in the water column, +1 descending, and 0 indicates periods when the AUV is stationary. A low pass filter was used in order to prevent any small fluctuations in sea water pressure to be recorded as a dive or resurfacing (Figure 9).

Once the raw data was sorted into ascending, descending, and stationary modes, profiles were created. A single profile consists of one vertical transect of the water column by the vehicle. For each profile, the raw data were binned in 1 meter depth increments with a maximum depth bin of 110 m. The red 'o' on Figure 10 indicate the locations of profiles of Tethys's raw measurements.

Next, individual profiles were combined in to sections which illustrate one complete horizontal transect offshore or onshore. These sections were identified by looking at changes in longitude and in some cases demarcated by visual inspection. The start and stop of each transect is indicated by a green 'x' in Figure 10. Each transect illustrates a cross- shore snapshot of temperature and optical backscatter during that particular YD. Tethys data set consists of twenty-nine sections, however, due to limited data in certain sections only 17 sections were used for this analysis. Tethys was deployed for only six days during the Monterey Bay experiment, yet produced an extremely high-resolution data set. With such a large data set it was valuable to focus on adjacent sections in time that illustrated a significant change in the evolution and propagation of sediment near the seabed.

In order to illustrate the temporal evolution of the water column during the experiment, Tethys data was also organized into time and depth sections at specific water depths and cross shore locations. Raw data was assigned to water depth sections ranging from 30 m to 100 m. The average line of latitude that Tethys flew was used to determine intersecting lines of longitude that correspond to depths of interest, i.e. depths of heightened optical signature. Once the desired location was found, the raw data taken over these particular locations was extracted and compiled in to a time series. A temporal view of the entire experiment helps draw focus to specific days of heightened activity as well as the effect that differences at the selected locations cross-shore.

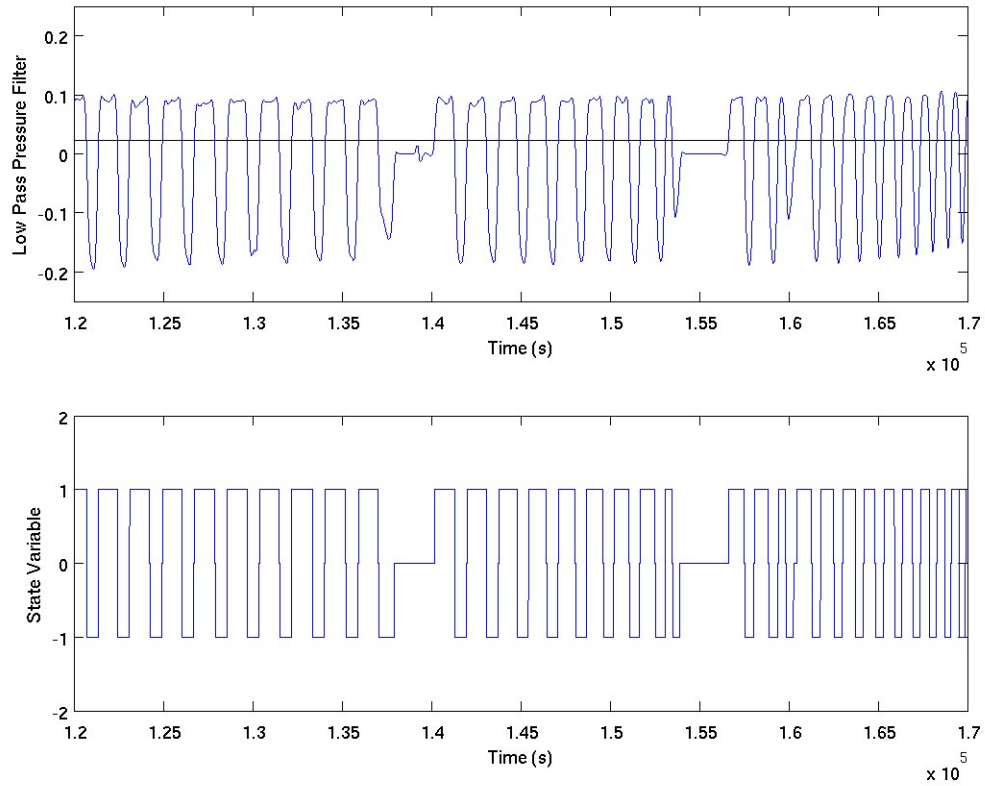


Figure 9. Changes in sea water pressure established Tethys location relative to the surface of the water. The first plot is low-pass filter pressure used to smooth out raw data and ensure small fluctuations in sea water pressure were not improperly categorized as a dive or surfacing. The second plot illustrates the AUV's motion in the water column. At 'state' of + 1 the instrument is diving, at -1 the AUV is ascending, and at 0 the AUV is stationary.

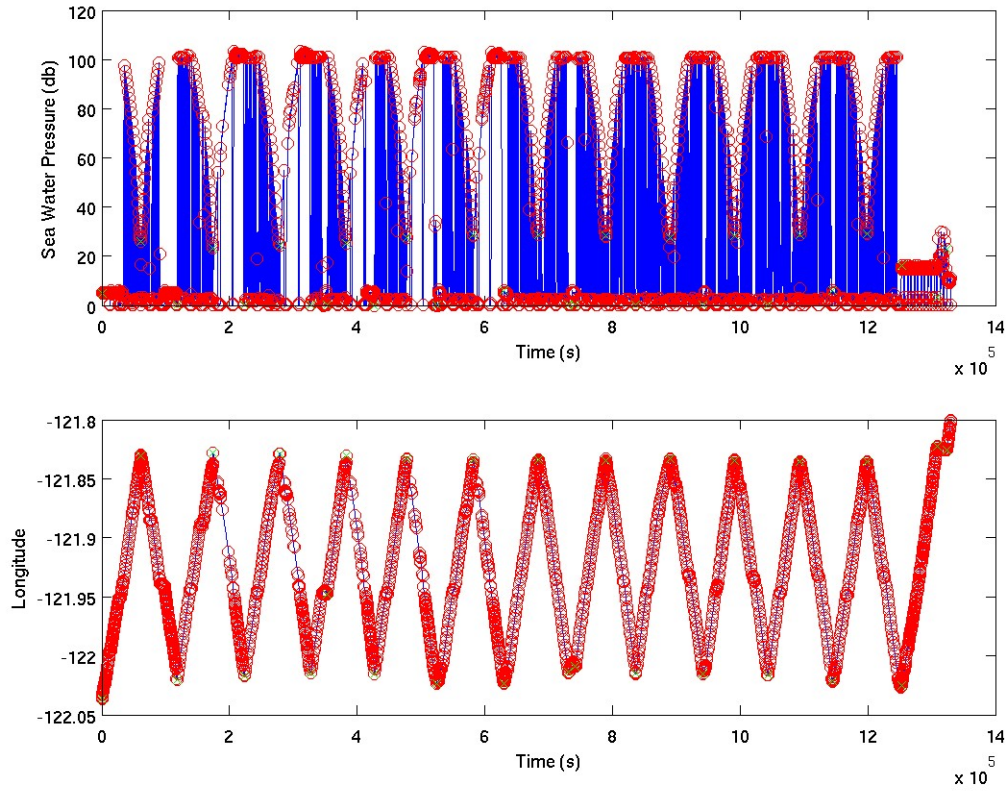


Figure 10. Example of the results of the profile and section identification algorithms used to separate raw data points into profiles and sections according to the AUV's relative location in reference to the surface of the water. The solid blue lines indicated sea water pressure. The red circles mark the beginning of vertical profiles. In the bottom panel, the start and stop of a cross-shelf sections are denoted by green 'x's.

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III. RESULTS

A. OCEANOGRAPHIC PROCESS

During the spring and summer months, the typically persistent Northwest winds present in Monterey Bay characteristically result in an upwelling environment with a strong uniform cross shelf stratification. During the course of the 2011 experiment, Monterey Bay experienced a shift in winds propelling a period of downwelling. Both the moored instruments and AUVs captured raw data during this transition period and the analysis of the temperature data during the transition period will help determine the relationship between wind forcing events and their subsequent effects on the ocean's stratification and internal wave propagation. Comparing ocean processes present in the water during periods of both strong and weak stratification enable conclusions to be drawn as to the stratification conditions necessary for the generation of ITB.

1. Wind Forcing

In Monterey Bay, winds are predominately from the Northwest. Wind speeds collected from NDBC buoy 46042, located at 122.46° W, indicate that these Northwestern winds are present during the initial days of the experiment and last from YD 285 until YD 288 (Figure 11, top panel). The wind buoy data denotes a shift in wind direction on YD 288 lasting until YD 290. The effects of this wind reversal on water column properties are present in the temperature and optical time series from the SeaHorse moored profiler (Figure 11, bottom panel). During upwelling, the warmest waters are confined to depths of 20 m however, beginning on YD 289 the warm surface waters penetrate to depths as deep as 50 m as downwelling forces warmer surface waters onshore. A strong correlation exists between the wind shift and the fluctuation of near surface temperature. The shift in wind direction marks the transition from a period of upwelling, responsible for the transportation of cold nutrient water to the surface, to a period of downwelling which forces warm water deep in to the water column. The downward propagation of warm water deep in the water column is apparent on YD 290 and consistently remains at deep depths until the end of the Tethys sampling.

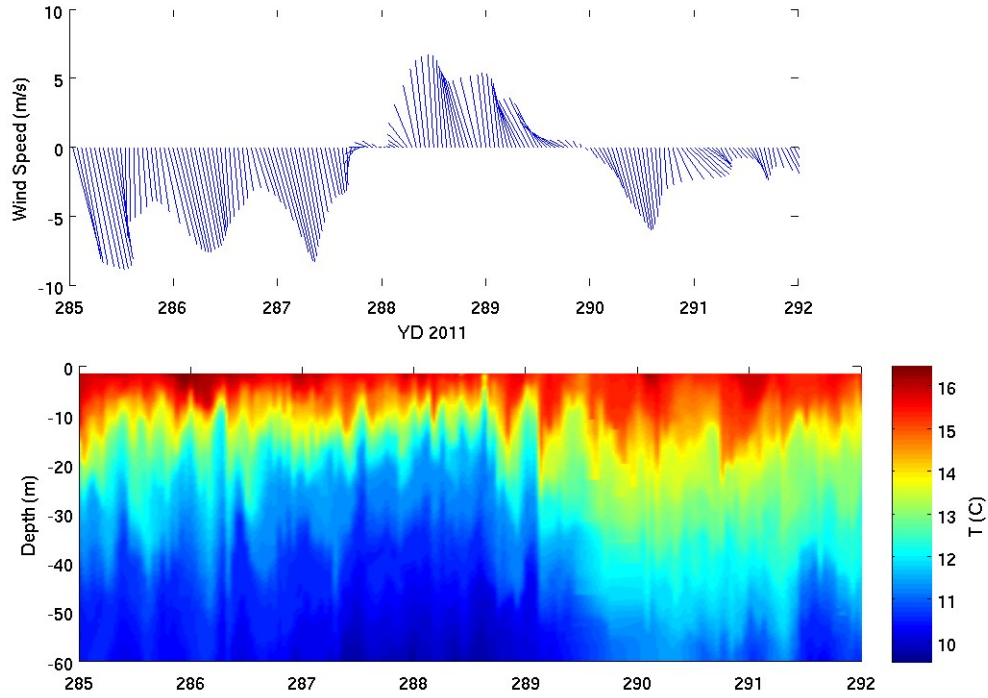


Figure 11. (Top panel) Wind speed vectors from NDBC Buoy 46042. YD 288 to YD 290 denotes a period of onshore Ekman transport and a shift from upwelling to downwelling. (Bottom panel) SeaHorse temperature timeseries. On YD 289 the strong shallow stratification begins to weaken with warm water penetrating deeper in to the water column weakening the stratification over 70 m depth. This weak stratification is present until YD 292.

2. Stratification

Monterey Bay experiences a strong near surface stratification during the spring and summer approximating a two-layer system due to extended periods of upwelling and solar warming of the surface layer. The SeaHorse time series profile illustrates this strong and shallow stratification from YD 285 to YD 288 with the warmest waters confined to the shallowest 10 m depth range, resulting in the presence of a strong near-surface temperature gradient. Beginning on YD 290 the temperature time series displays a dramatic stratification change with warm waters, typically confined to the top layers of the ocean, forced to depths near the seabed (Figure 11). The T-chain temperature

timeseries also indicates significantly warmer waters present in the water column on YD 290 (Figure 12). The coldest isotherm present on this day is 11° C. There is approximately a two-day time lag before the effects of the shift in wind direction are clearly displayed in the stratification in both the T-chain and SeaHorse. Despite this time lag, a strong relationship can be drawn between the shift in wind and the weakened stratification in Monterey Bay. The previously strong near surface stratification, which prevents wind driven motion from penetrating deep into the water column, is heavily affected by the reversal of winds (Tjoa 2003). In order to determine whether the weakened stratification at 70m depth is uniform across Monterey Bay during the downwelling period, the SeaHorse and T-chain temperature timeseries are compared to Tethys cross-shore transects during these particular year days.

Figure 13 is a Tethys transect taken on YD 287, prior to the shift in wind direction. The stratification present across the shelf is uniformly strong with a high temperature gradient. This cross-shore temperature data correlates with the data collected by the moored profilers at 70 m, indicating the presence of a strong shallow near surface stratification on YD 287. Both the T-chain and SeaHorse temperature data show a period of weakened stratification at 70 m depth on YD 290. Figure 14 illustrates Tethys cross shore temperature measurement on this particular day. The cross shelf stratification is noticeable weaker than the stratification present on YD 287. The stratification is no longer uniform across the entire shelf, with significantly weaker stratification located near shore as compared to the presence of a strong offshore stratification. The water column at 70m depth experiences typically warm surface waters at depths as deep as 60m, while the water column at 100 m has begun to return to strong stratification conditions with warm waters confined to the top 10 m of the water column.

During the initial period of upwelling, the temperature data from the moored profilers matches the cross-shore temperature data from AUV revealing a period of uniform stratification across the entire seabed. During the period of downwelling however, the temperature measurements extracted at 70m were not similar to the conditions spanning the entire shelf. The locations of both moored instruments experienced a period of a

significantly weakened stratification that was not strongly present at greater depths. This discontinuity present across the shelf during the transition from downwelling to upwelling will be the topic of further discussion.

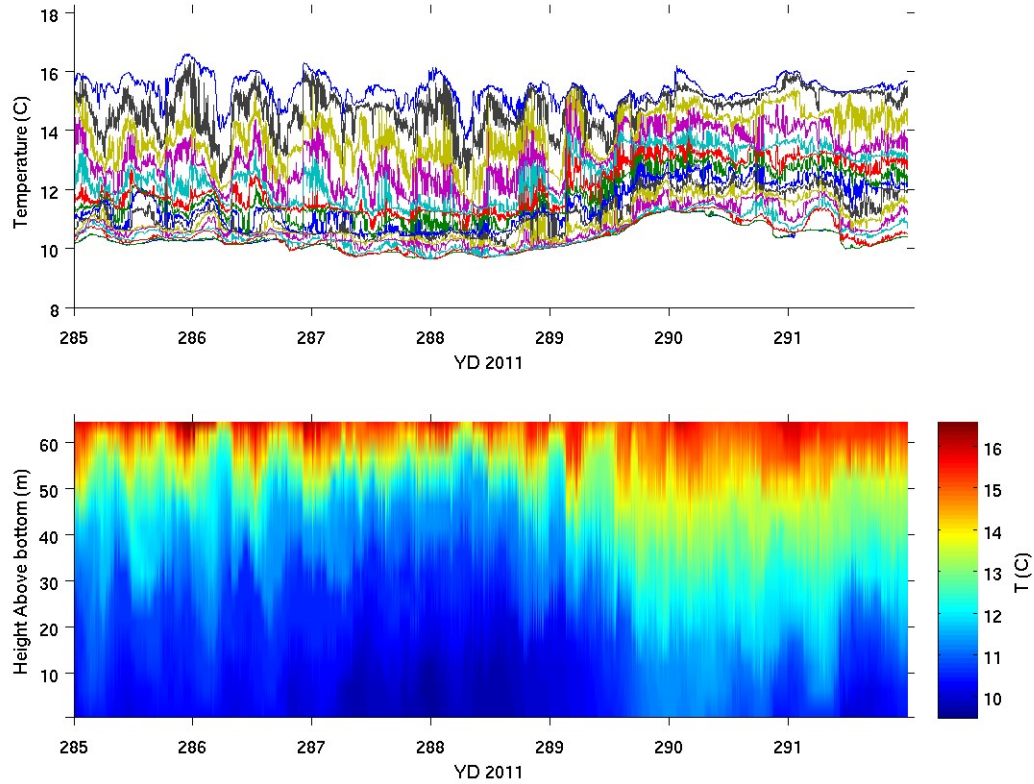


Figure 12. T-chain temperature time series from YD 285 to 292. (Top panel) Temperature time series from the individual sensors on the mooring. Each color corresponds to a different sensor. The largest change of temperature near the sea bed occurs on YD 290, when significantly warmer water is present near the bottom. The second plot illustrates the T-chain temperature as a time-depth section. The warm waters present on YD 290, which are typically confined to shallow depths, penetrate depths as deep as 60 m.

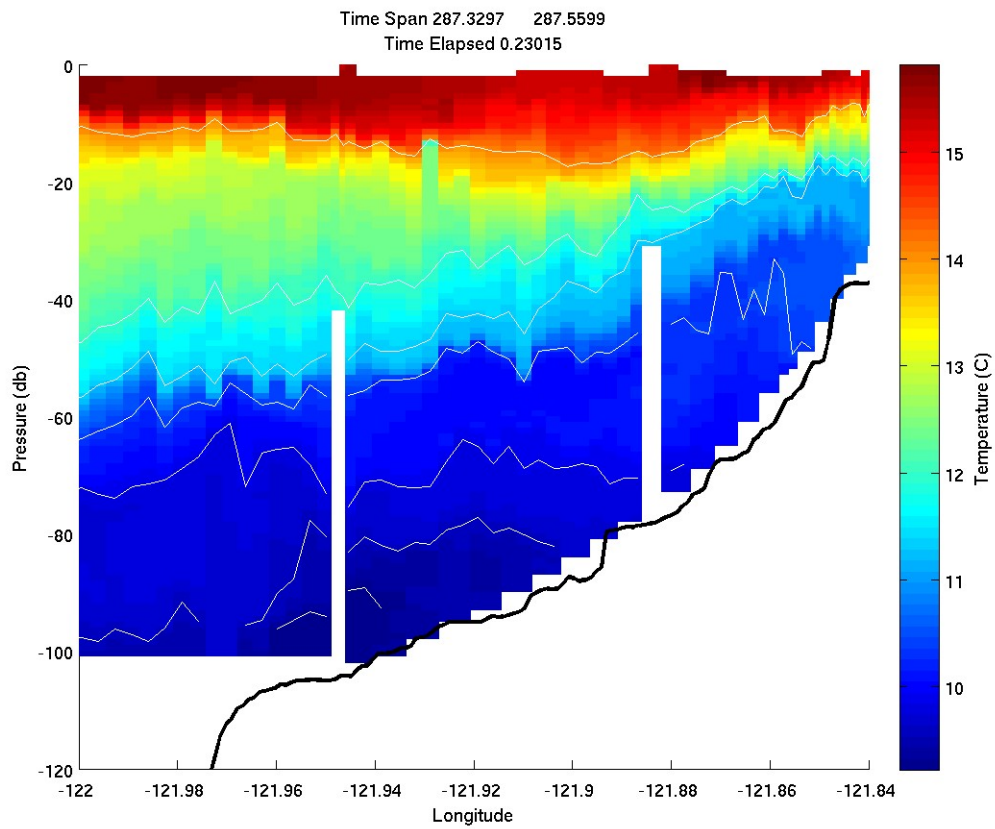


Figure 13. Tethys temperature data extracted from YD 287.3297 provides a cross shore illustration of the stratification in Monterey Bay during the initial period of upwelling. On this YD the strong shallow stratification is uniform across the shelf.

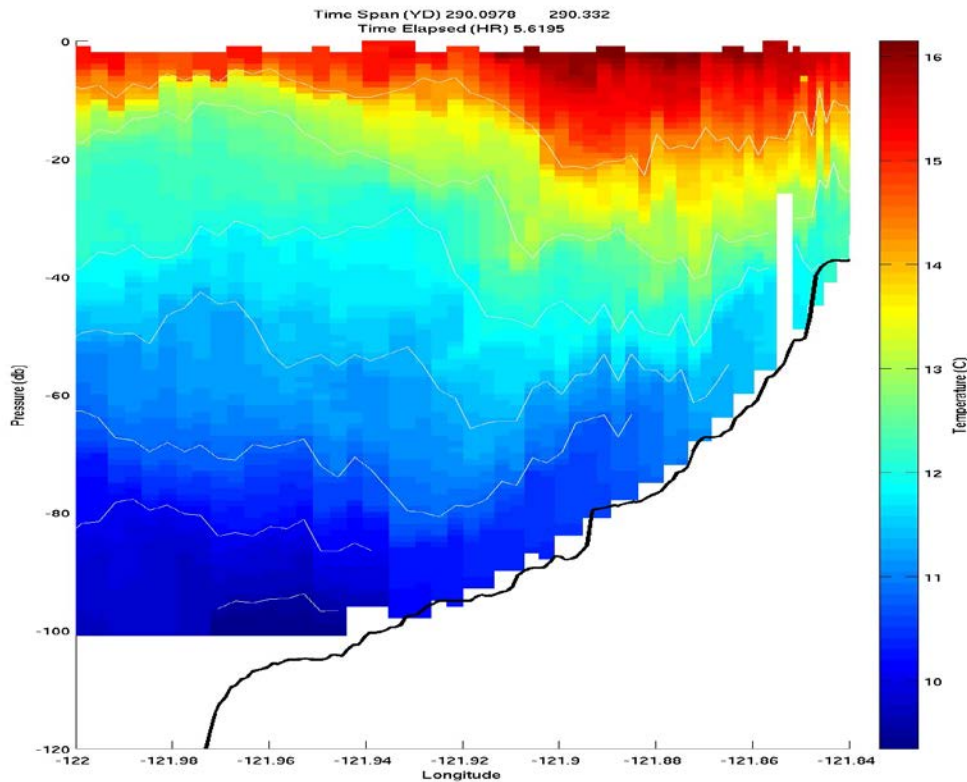


Figure 14. Tethys temperature data extracted from YD 290.0976 provides a cross shore illustration of the stratification in Monterey Bay during the second period of upwelling. The cross shore stratification is not uniform across the shelf, with a significantly weaker stratification present near shore.

3. Salinity

High temperature values and low salinity measurements that occur at the surface contribute to the presence of strong shallow stratification (Tjoa 2003). Salinity values are typically constant in Monterey Bay during the upwelling season with density controlled by the temperature of the upper surface layers (Woodson et al. 2011). A series of the SeaHorse density profile data from YD 285 to YD 290 illustrates the evolving density throughout the experimental period (Figure 15). These profiles represent the average density on a single YD. The first three YDs indicate a period of a steep density gradient

extending 20 m down the water column. This steep gradient gradually flattens out and is essentially nonexistent on YD 289. On YD 290 the bottom depth experiences a slight decrease in density, which correlates with the SeaHorse's temperature data.

The Brunt Vaisala frequency quantifies the structural changes of stratification (Figure 16). Initially the density structure found in Monterey Bay approximates a two-layer system with warm water contained in the near surface layers and cool water contained at deeper depths, typical during the spring and summer season. From YD 285 to YD 287 a pronounced near surface N_{\max} is present, which correlates with classical conditions during a period of upwelling. The second row of Figure 16 illustrates the buoyancy frequency when the ocean conditions change to a downwelling environment. During the period of downwelling, the three days experience significantly weakened N_{\max} values that descend down the water column. The Brunt Vaisala frequency is dependent on the density gradient. During periods of downwelling this gradient weakens due to the vertical dispersal of buoyant waters. The weakening and deepening of N_{\max} denotes the presence of a weak stratification which are typical of conditions found during periods of downwelling. The wind forcing returns to upwelling conditions on YD 290 and this transition is noted in the final graph of Figure 16 on YD 292. The two day time lag between the shift of winds and the restratification is again noticeable in the buoyancy frequency profiles that represent the strength of the ocean's stratification.

Due to the problems with the Tethys conductivity sensor, there is no reliable data to mathematically calculate the buoyancy frequency found cross shore in Monterey. This data would have allowed an additional comparison between the strength of stratification present at deeper depths and shallower depths confined to 70 m.

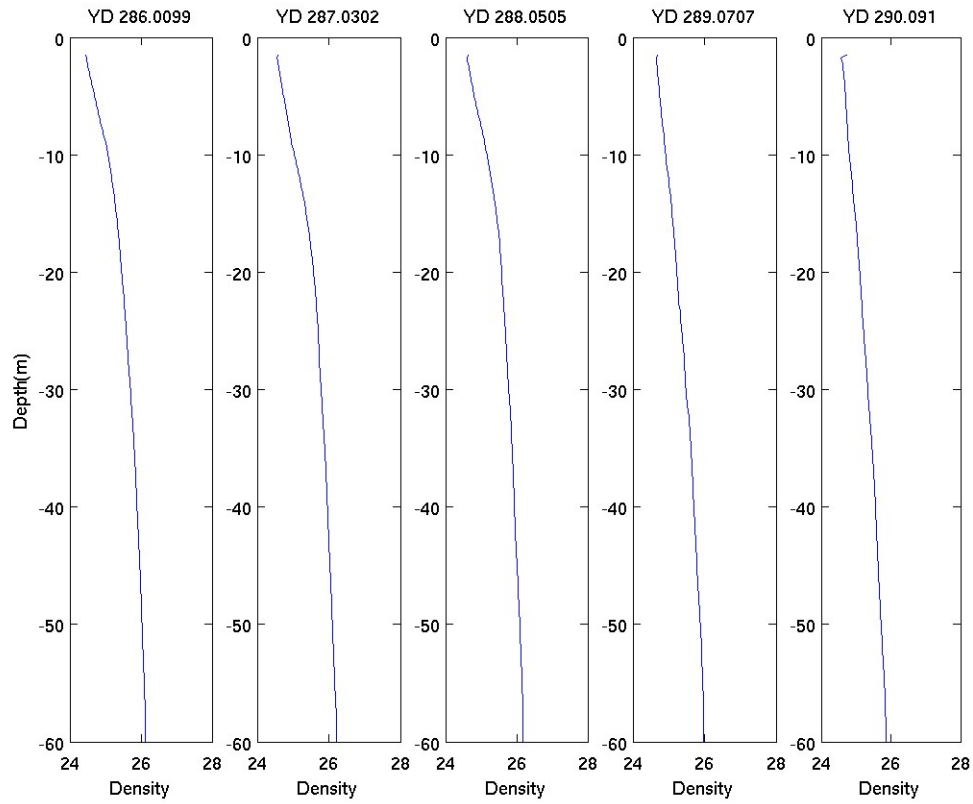


Figure 15. SeaHorse density profiles from YD 286 to YD 290 illustrate the presence of uniform density from YD 286- YD 288. A steep density gradient extending 20 m is present during these days, yet flattens out during the next two days. The weak gradient is characteristic of a downwelling environment.

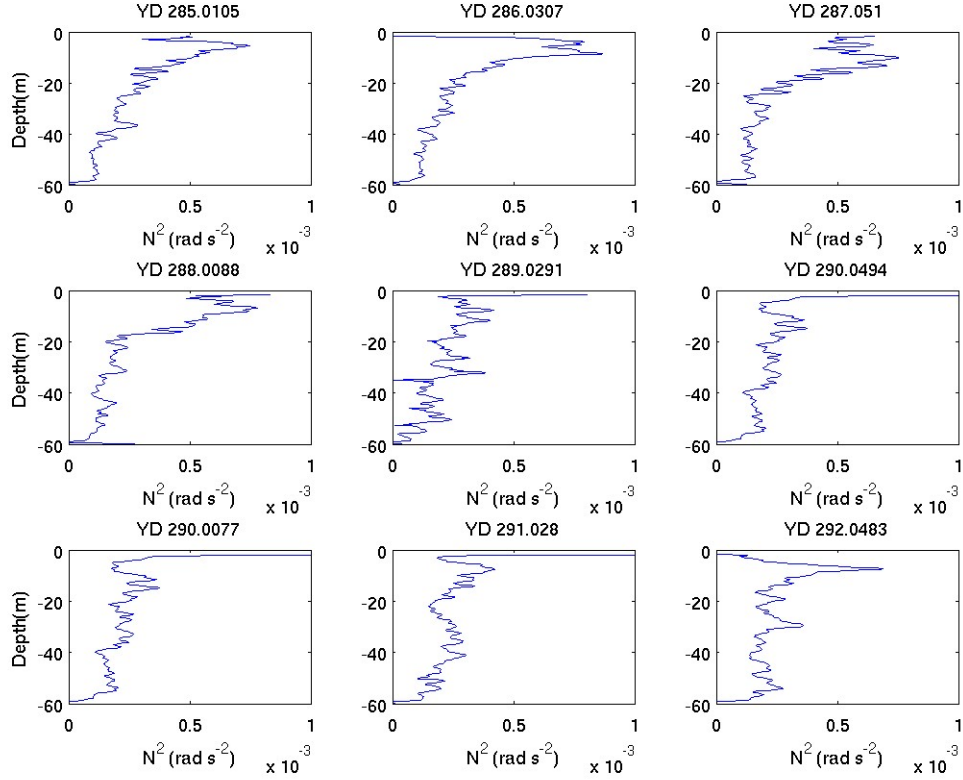


Figure 16. Series of Brunt- Vaisala frequency profiles derived from SeaHorse data. The raw data was binned into one day intervals spanning the entire experiment. The first row illustrates the presence of a strong shallow buoyancy frequency during initial upwelling conditions beginning on YD 285. The second row illustrates the presence of a weak and no- existent N_{\max} , which is characteristic of a downwelling environment beginning on YD 288. The third row corresponds to the second period of upwelling, with the returned presence of a strong shallow N_{\max} on YD 292.

B. SEDIMENT RESUSPENSION

1. Near-Bed Turbulent Mixing

The use of several instruments during the 2011 experiment ensured that data would be collected at numerous depths along the seafloor in order to determine the location of maximum near-bed suspension. The SeaHorse collected data at 67.5 m depth. The location of this moored instrument was chosen due to the composition of material that makes up the seabed. 70m depth (36.7286° N, -121.8722° W) marks the location of

Monterey's "mud belt" and during times of heightened stress near the sea bed, the muddy seabed particulates are easily entrained into the water column. The results from the moored profiler over this specific depth provide high resolution data to establish the vertical structure of benthic material present in the water column (Figure 17).

The measurements taken from Tethys allows for a temporal and spatial analysis of the concentration of suspended near-bed material. Figure 18 illustrates the particulate density from YD 285 to YD 292 taken at 70 m depth. Tethys optical data reveals the presence of a heightened particulate load present from YD 285 to YD 289. This heightened optical backscatter in the water column is also found in the SeaHorse data spanning the same duration. The Tethys temperature time series denotes that strong shallow stratification is present during the period of enhanced near-bed concentration of sediment. At the shallow depth of 70 m both the moored and mobile instruments captured the heightened presence of near-bed particulates, however the second depth chosen to analyze was only sampled by the AUV transects.

Figure 19 illustrates the particulate density from YD 285 to YD 292 taken at 100 m depth (36.7286° N, -121.9394° W). This particulate depth is of interest to this experiment due to its close proximity to the steep continental shelf break. Measurements taken at deeper depths near the shelf break are intended to capture deeper ocean processes in order to determine the effects that these processes have on enhanced mixing in the water column and the presence of INLs. The heightened particulate signature found during the initial period of upwelling is similar to that found at 70 m depth, although is not as large. More noticeable, however, is an enhanced particulate load found during the second period of upwelling from YD 289 to YD 291. This enhanced signature is not present in the data extracted over 70 m depth and could be the result of the discontinuity of stratification found across the shelf.

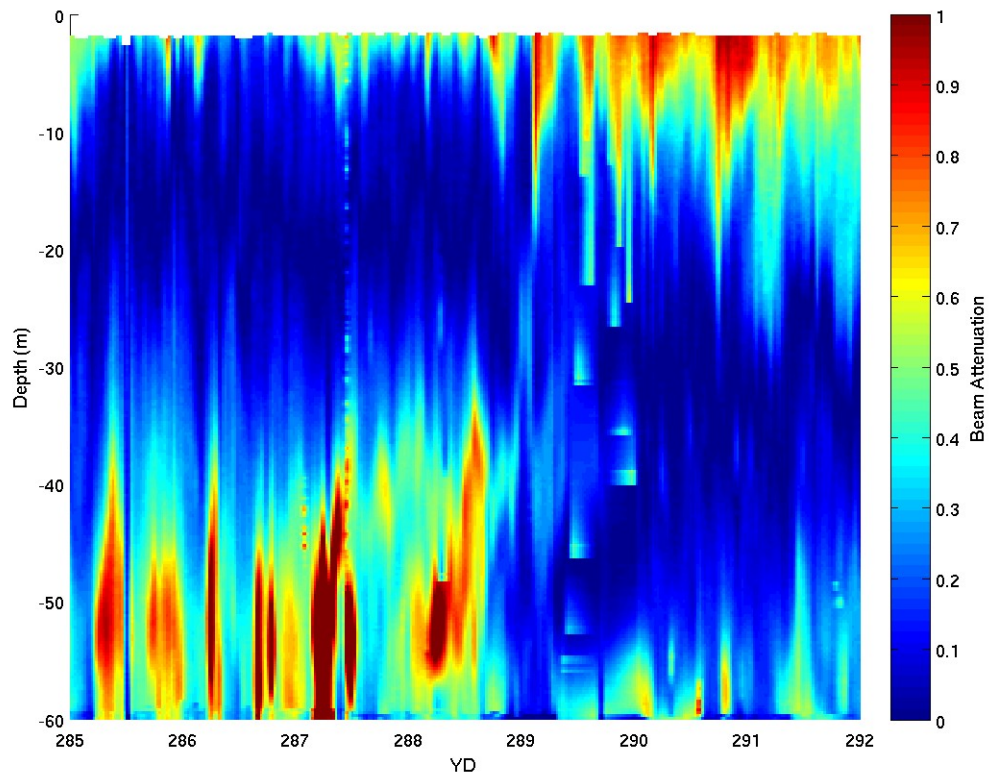


Figure 17. SeaHorse optics time-depth section indicating heightened periods of sediment concentration at 70 m water depth. The enhanced signature of particulate load from YD 285 to YD 288 corresponds to the initial upwelling period when a strong shallow stratification was present near shore.

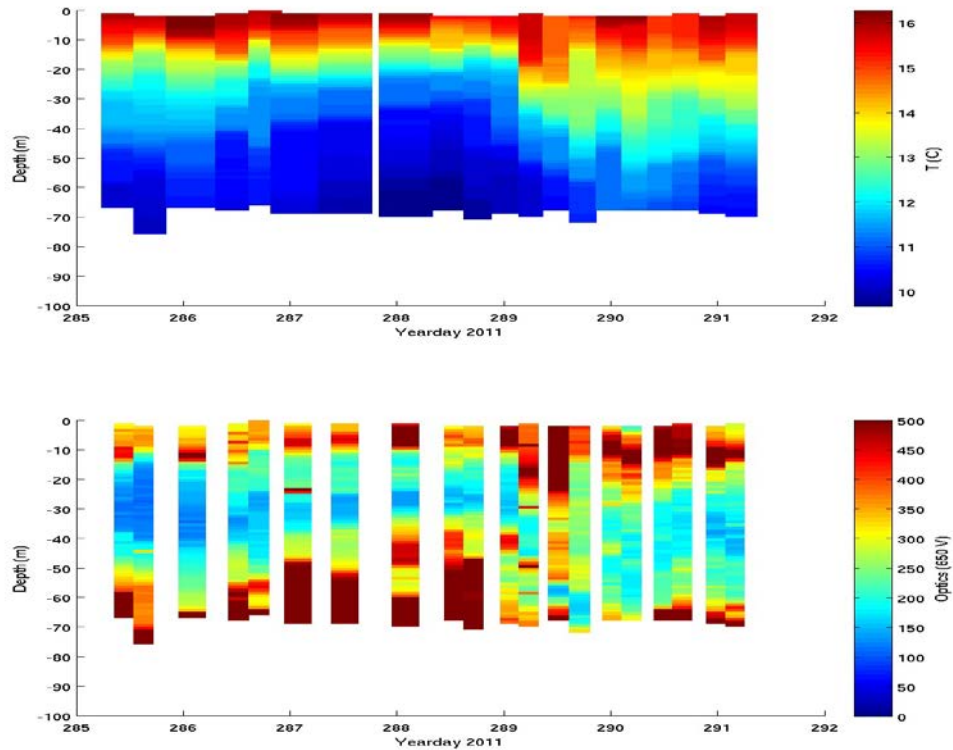


Figure 18. Time-depth section of Tethys temperature (top) and backscatter data (bottom) recorded at 70 m depth from YD 285 to YD 292. The temperature time series reveals a strong near surface stratification from YD 285 until YD 288 where the stratification weakens and deepens through YD 291. The backscatter time series indicates the largest amount of particulate load in the water column occurred between YD 287 to YD 289.

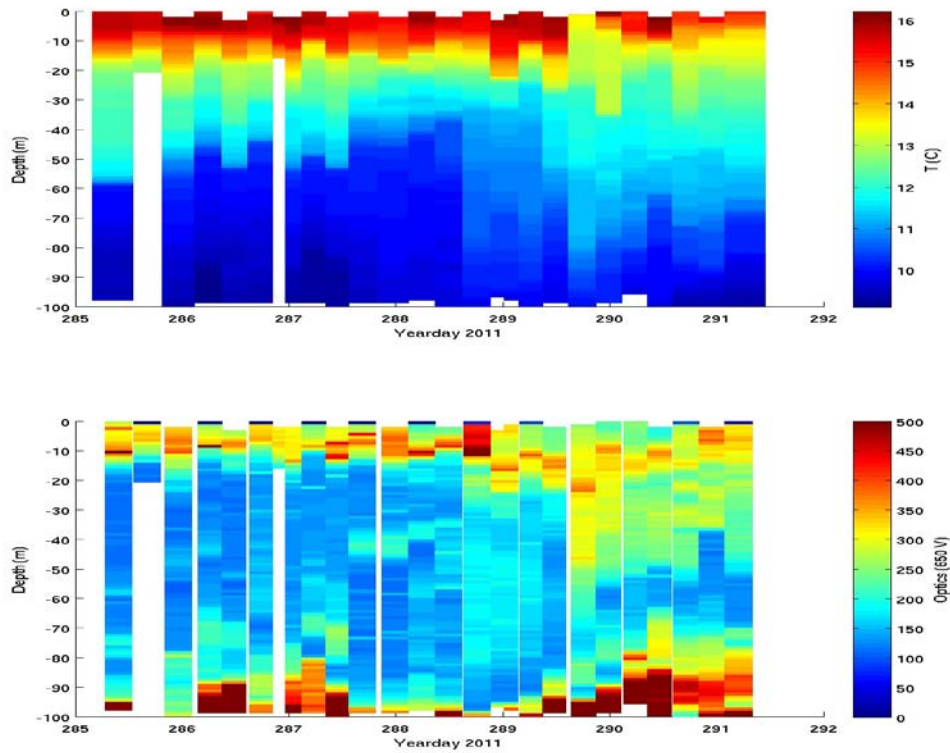


Figure 19. Time-depth section of Tethys temperature (top) and backscatter data (bottom) recorded at 100 m depth from YD 285 to YD 292. The temperature timeseries reveals a strong near surface stratification from YD 285 until YD 288 where the stratification weakens and deepens until YD 291. The backscatter timeseries indicates the largest amount of particulate load in the water column occurred between YD 290 to YD 291.

2. Particulate Load Concentration

A temporal view of Tethys particulate signature, displayed in Figures 18 and 19 provide a view of when an enhanced sediment load was present during the experiment, but a spatial analysis of the data is necessary in order to determine the location of maximum near-sea bed suspension. Figure 20 is a cross-shore view of the concentration of particulates located in Monterey Bay. The first plot is Tethys raw particulate measurements averaged over 0 to 10 meters above the seafloor. The second plot recasts

the information displayed previously by averaging and binning the raw data points to provide a more clear analysis on where the concentration of sediment was located cross shore.

The different colors correspond to optical backscatter data extracted during the three different environments found in the ocean during the course of the experiment. The black dots and line indicates measurements taken at the beginning of the experiment from YD 285 to YD 287 during a period of upwelling. The density signature during this initial period of upwelling contains the largest particulate signature with a concentration of measurements confined to locations near the “mud belt” at 70 m depth. From YD 288 until YD 290 Monterey Bay experiences a shift in wind direction propelling a period of downwelling, with green figures indicating measurements extracted during this ocean environment. The particulate load concentration is still confined to shallow, near-shore depths of 70 m, yet is not as strong as measurements taken during the initial period of upwelling. The most noticeable difference with the points taken during downwelling conditions is the significant decrease in sediment suspension traveling offshore. The red data points indicate measurements taken from YD 290 to YD 292, which spans the return to upwelling conditions in Monterey Bay. Unlike the previous particulate measurements taken during the initial upwelling conditions, there is no signature of a heightened particulate load across the entire shelf.

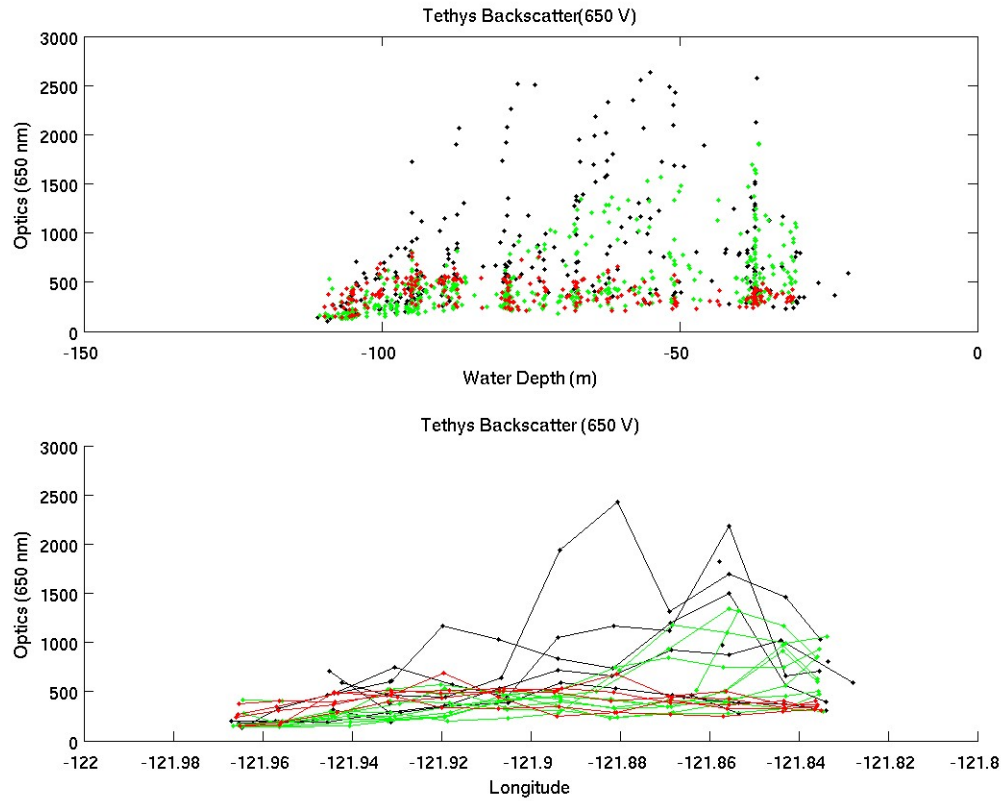


Figure 20. Tethys optical backscatter captured cross-shelf from YD 285 to YD 292. The first graph is the raw measurements collected 10 m above the seabed. The second plot recasts this information by averaging the raw measurements into cross shore bins. The black points indicate data sampled during the initial upwelling period from, YD 285 to YD 287. This data contains the largest signature of particulate load in the water column. The green points are data collected during downwelling conditions, from YD 288 to YD 290. The red values indicate data sampled over the second upwelling period from YD 290-292.

C. INTERMEDIATE NEPHELOID LAYERS

In order to illustrate this sediment suspension and propagation, Tethys temperature and optical measurements were plotted spatial across Monterey Bay. The information provided by the various sensors on the Tethys AUV provides highly resolved information to identify several components that could affect the generation and propagation of intermediate nepheloid layers.

Spatially tracking the particulate signature on YD 287 (Figure 21) illustrates the presence of a highly concentrated evolving mass located near the seabed at 70 m depth. The section also reveals a heightened particulate signature in the water column attached to the large concentration of material present at 70 m depth. This intermediate signature located in the water column extends cross shore to -121.94° W. Due to the lack of useable salinity data from the Tethys, the optical backscatter measurements are mapped on isotherms instead of isopycnals, revealing that the intermediate nepheloid layers are confined to 10 degree isotherms as they advect offshore. On this particular YD the corresponding cross shore temperature reveals a uniformly strong shallow stratification present across the shelf.

The following Tethys transect (Figure 22) reveals a similar picture of the interior of the ocean, however, the high concentration of near bed material has propagated further onshore and the intermediate nepheloid layers have advected offshore past the continental shelf. Each transect covers roughly five and a half hours, and although they do not provide snap shots of internal ocean processes, they do provide an illustration for the propagation of internal nepheloid layers offshore. Figure 23 is the last Tethys transect taken during initial upwelling conditions. The strong shallow stratification is still present and the mass concentration of sea bed material is tightly confined to shallow depths. The presence of the internal nepheloid layers confined to 10 degree isotherms is still apparent but provides a much weaker optical signature than the previous two transects.

The next Tethys transect was taken during downwelling conditions, and there are significant changes in both the cross shore temperature data as well as optical readings. The previously strong shallow stratification is no longer uniformly present cross shore. Near the shore the stratification is significantly weaker, while traveling off shore the stratification is not as weak. The presence of intermediate nepheloid layers is no longer apparent in the Tethys optical data; however the presence of a near bed concentration of material is still located nearshore (Figure 24). These ocean characteristics remain intact during the subsequent Tethys transect in a downwelling environment (Figure 25).

YD 290 marks the shift in winds and Monterey Bay returns to upwelling conditions. Figures 26–29 illustrate the raw material captured by the Tethys transects

over this time period. Unlike the initial upwelling period (YD 285 to YD 288) there is no indication of an intermediate nepheloid layer present at shallow depths. Upon closer analysis, however, the presence of a deep offshore particulate layer is distinguishable in the large near-bed concentration of material at -121.94° W corresponding to 100 m depth. The presence of this heightened offshore particulate load is discernible through the end of the experiment on YD 292. Unlike the previous upwelling period, the concentration of near bed material does not propagate onshore, but stays confined to depths around 100 m. This could be due to the lack of a uniformly stratified ocean across Monterey Bay's shelf.

In order to closely analyze the particulate load present at 70 m throughout the experiment a time series of SeaHorse optical measurements was created (Figure 30). This plot indicates a heightened near-bed density signature during the beginning of the experiment in upwelling conditions. At the onset of the second upwelling conditions however, on YD 290 there is relatively no near sea bed signature present. The large difference in the optical measurements on shore at 70 m and offshore at 100 m could be due to the differing stratification present over each depth.

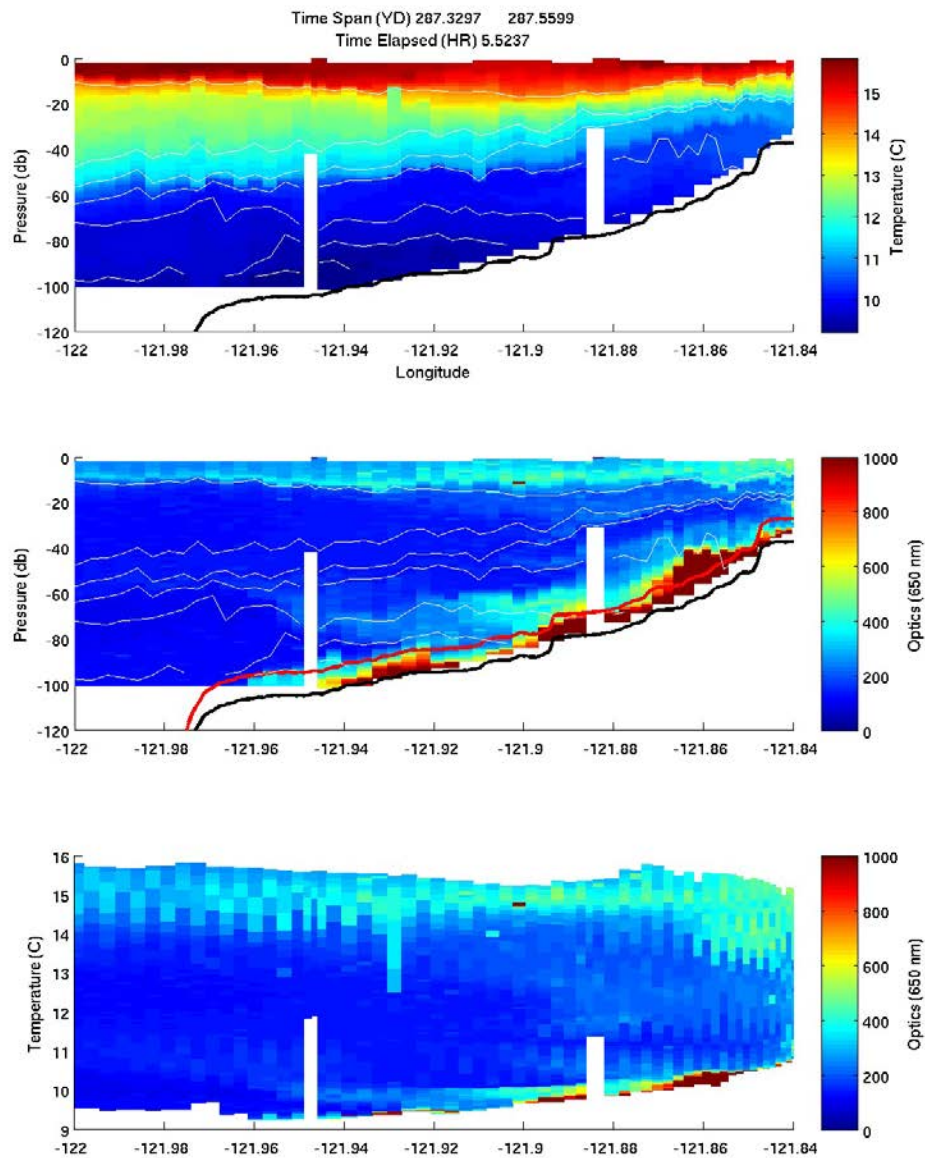


Figure 21. Tethys cross-shore temperature section collected on YD 287.3297 reveals the presence of a uniformly strong shallow stratification cross shelf. The black solid line represents the bathymetry of Monterey Bay and the black lines indicate isotherms spaced 15 m apart. The cross-shore section of optics illustrates a strong concentration of particulate load located at 70 m. The red line is the boundary set for the collection of near-bed sediment that is analyzed. The bottom plot is a time-temperature section of backscatter that illustrates particles advected offshore on a 10°C isotherm.

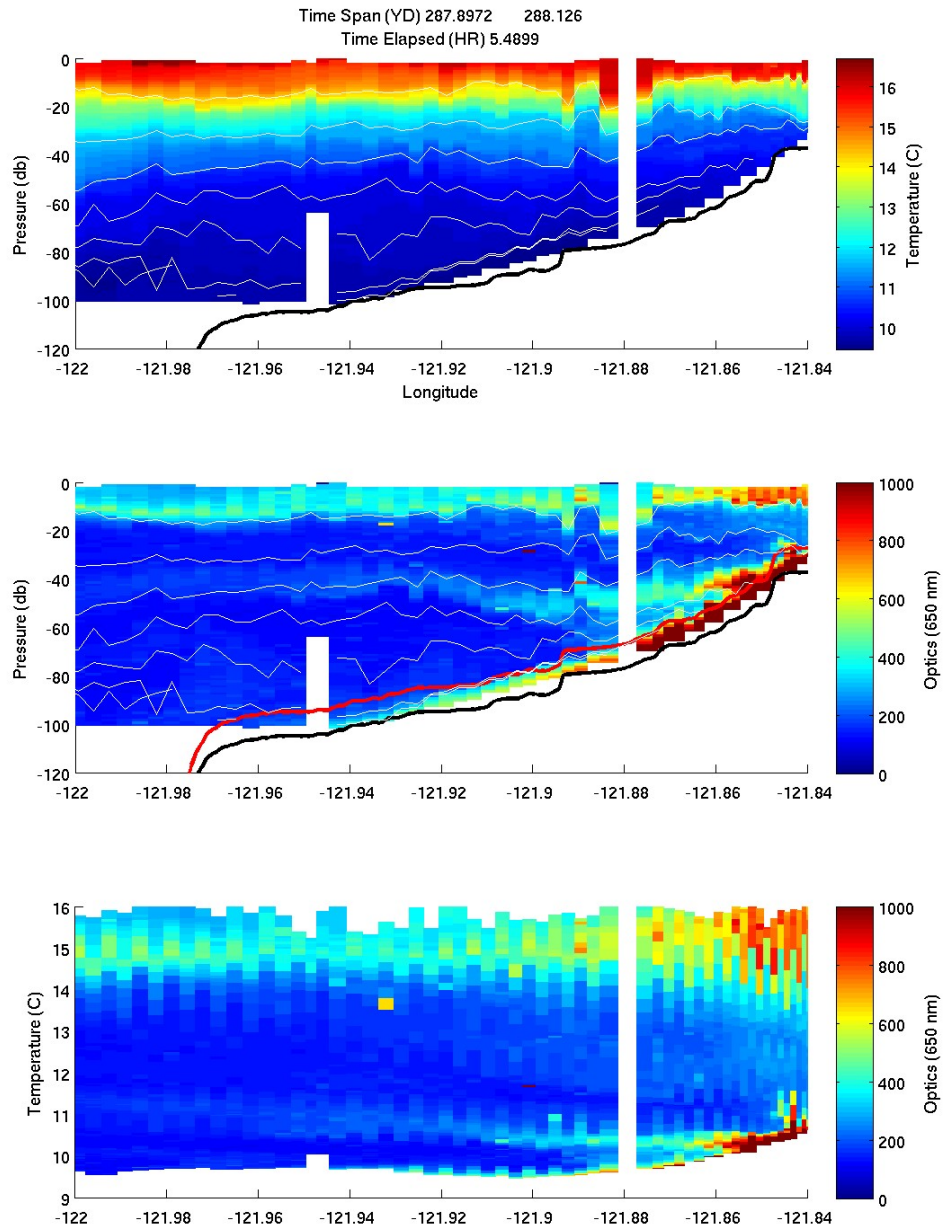


Figure 22. As in Figure 21 the cross-shore temperature section collected on YD 287.8972 reveals the presence of a uniformly strong shallow stratification cross shelf. The cross-shore section of optics illustrates a strong concentration of particulate load located at 70 m. The red line is the boundary set for the collection of near-bed sediment that is analyzed. The bottom plot illustrates particles advected offshore on an 11°C isotherm.

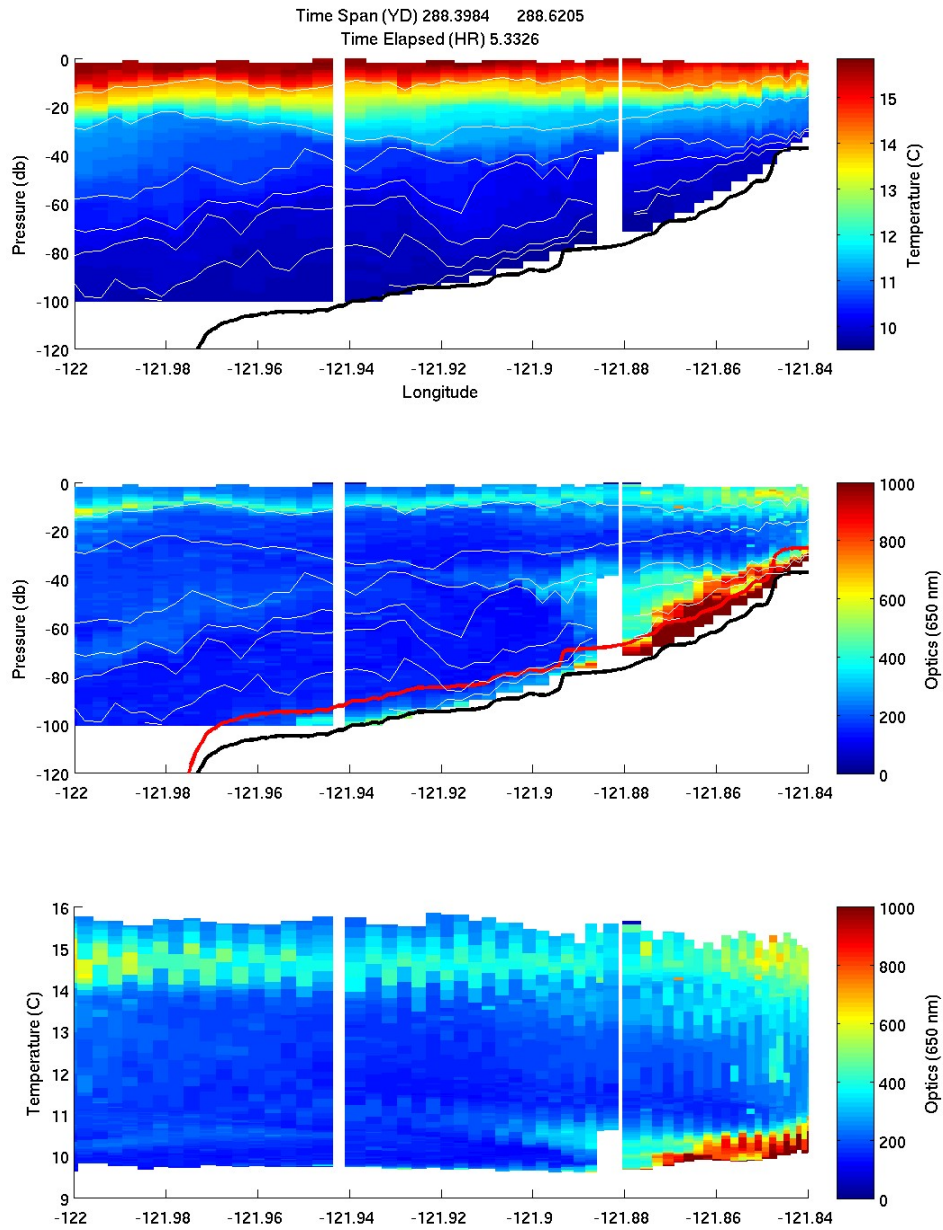


Figure 23. As in Figure 21 the cross-shore temperature section collected on YD 288.3984 reveals the presence of a uniformly strong shallow stratification cross shelf. The cross-shore section of optics illustrates a strong concentration of particulate load located at 70 m. The bottom plot illustrates particles advected offshore on an 11°C isotherm.

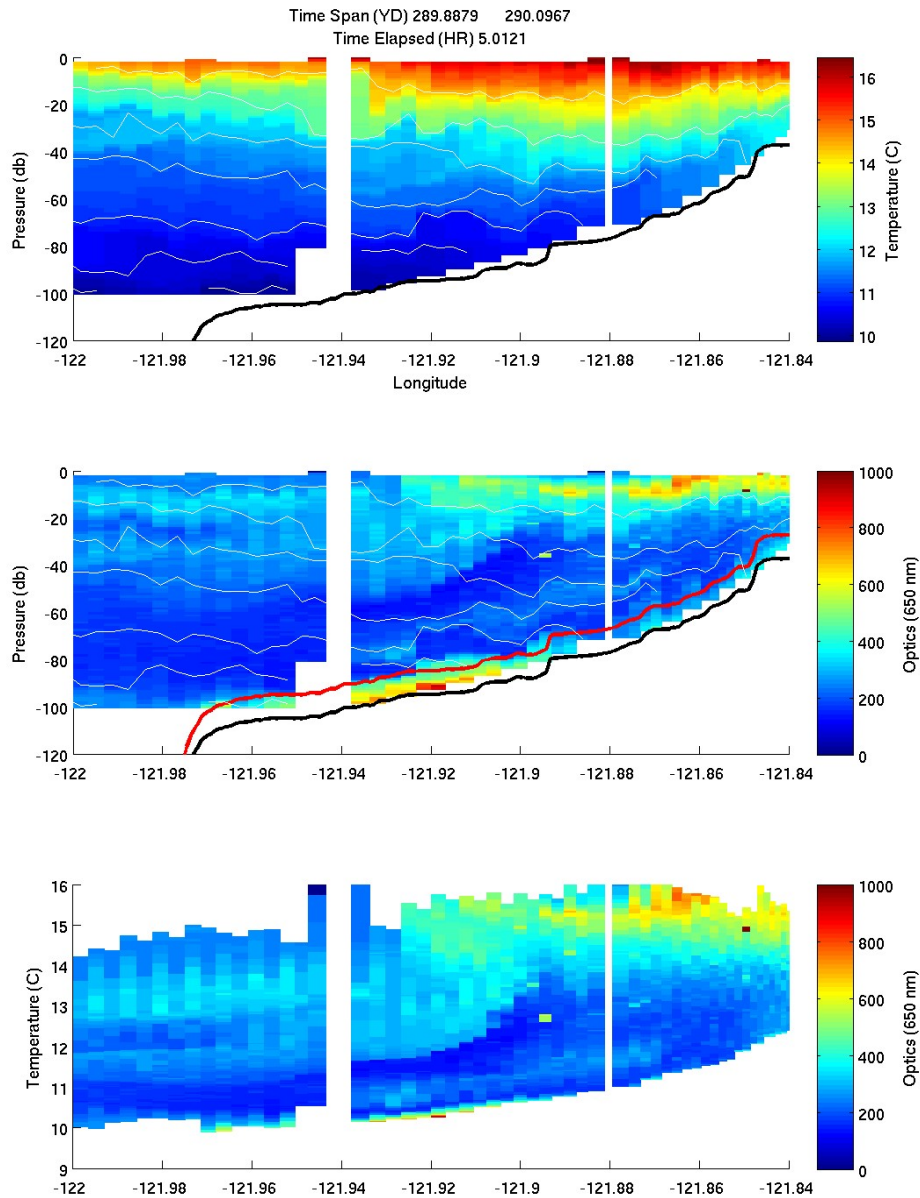


Figure 24. Tethys cross-shore temperature section collected on YD 289.8879 reveals the presence of a weakly stratified shelf. The cross-shore section of optics illustrates a weakened concentration of particulate load near the seabed. The bottom plot illustrates the absence of particles advected offshore on isotherms.

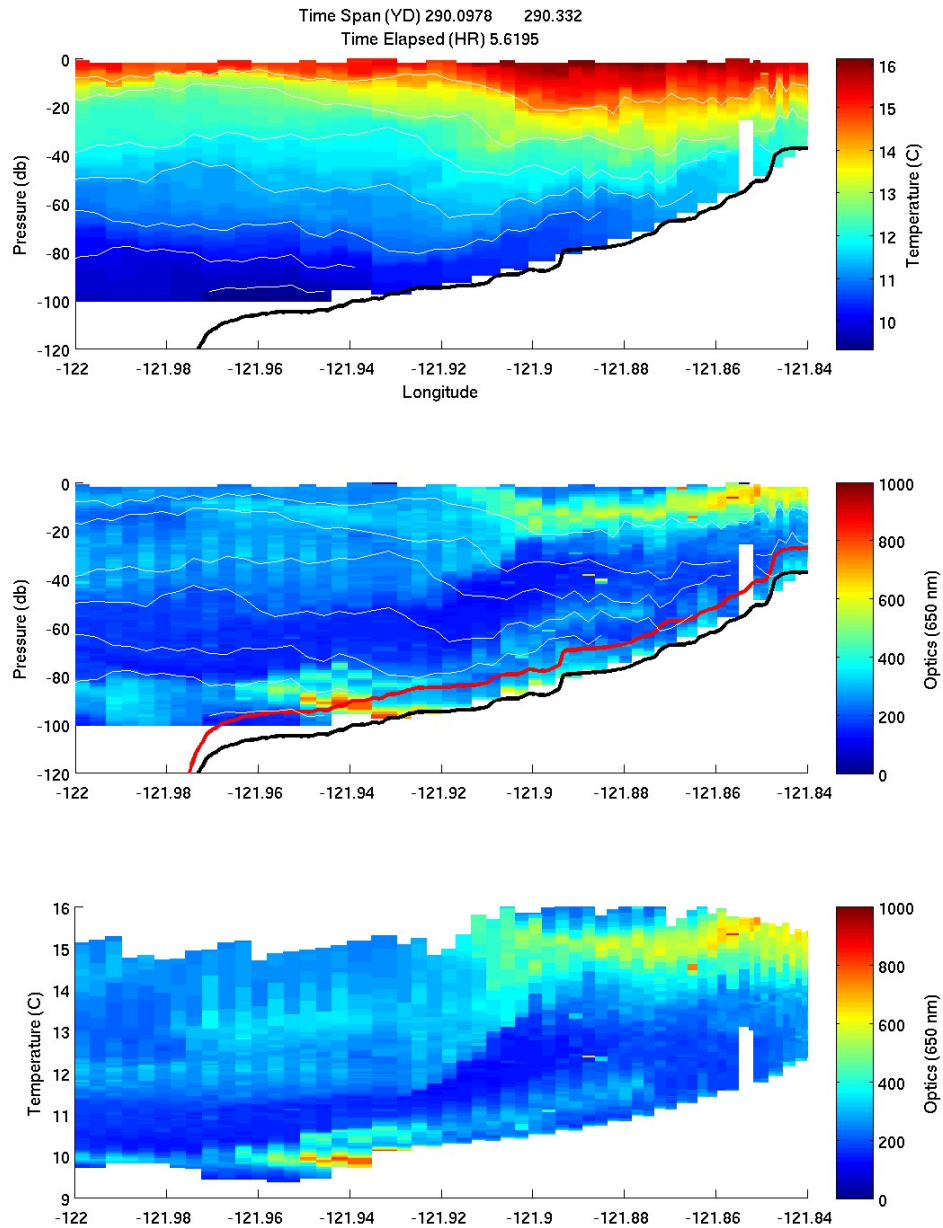


Figure 25. As in Figure 24 Tethys cross-shore temperature section collected on YD 289.8879 reveals the presence of a weakly stratified shelf. The cross-shore section of optics illustrates a weakened concentration of particulate load near the seabed. The bottom plot illustrates the absence of particles advected offshore on isotherms.

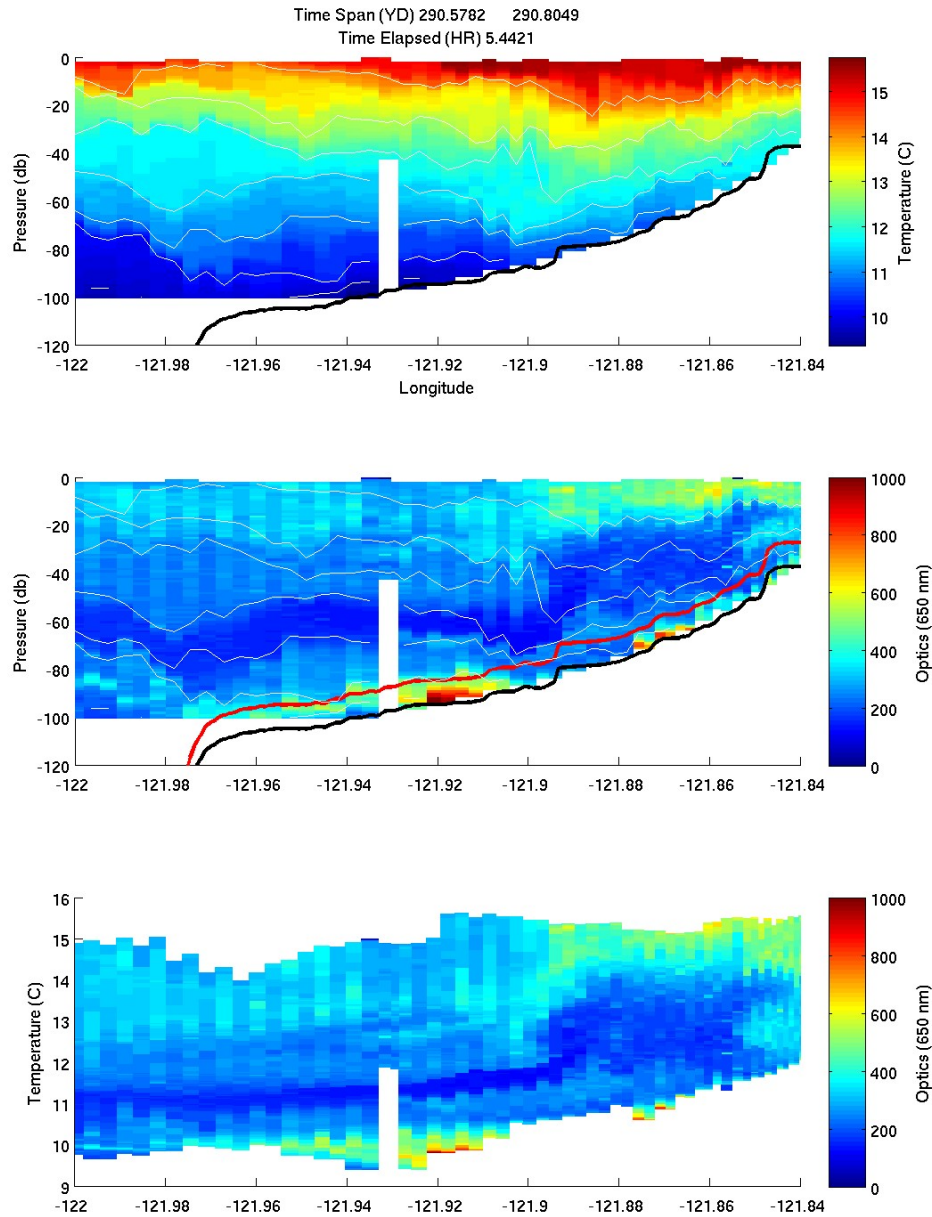


Figure 26. Tethys cross-shore temperature section collected on YD 290.5782 reveals the presence non-homogenous cross shelf stratification. The cross-shore section of optics illustrates a strong concentration of particulate load located at 100 m. The bottom plot illustrates particles advected offshore on an 11°C isotherm.

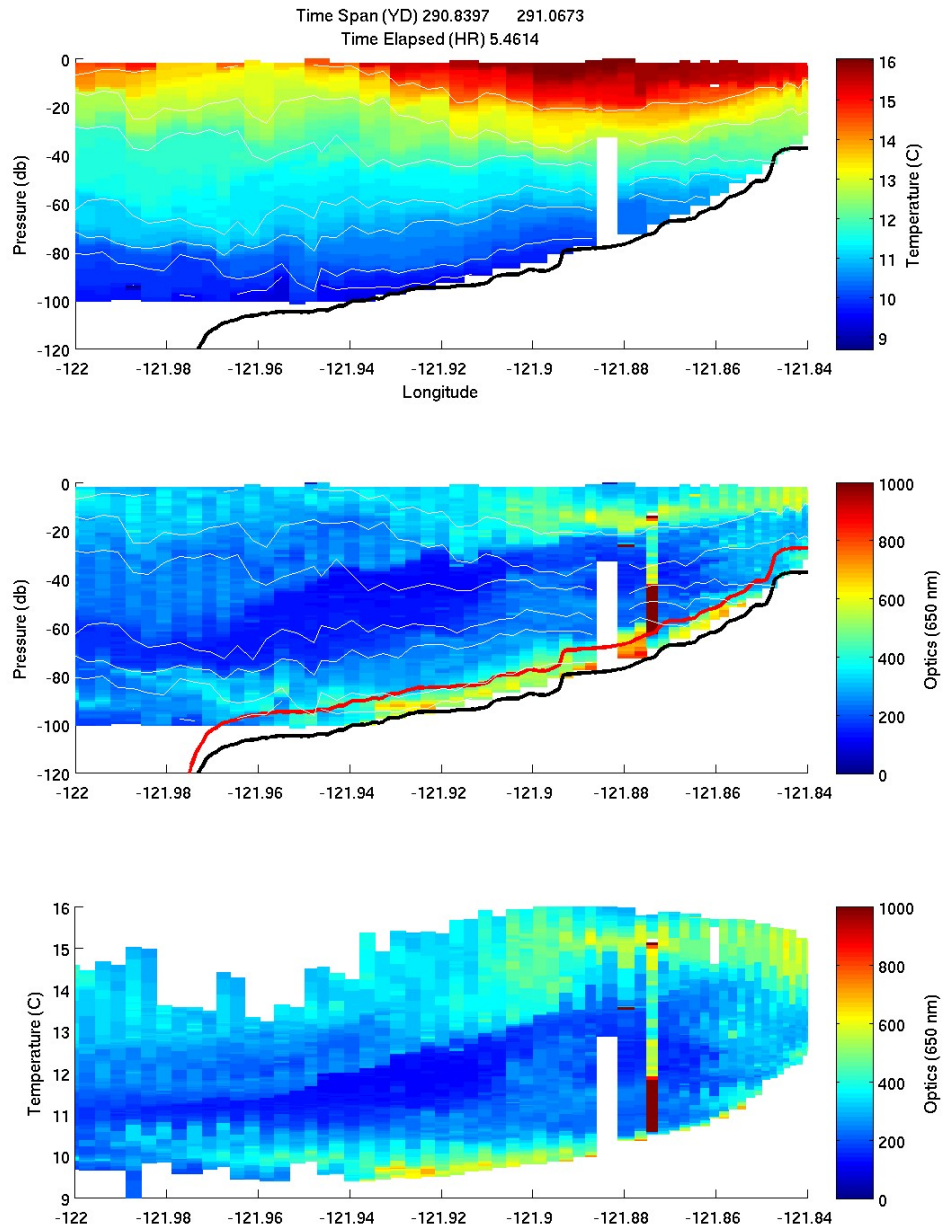


Figure 27. As in Figure 26 Tethys cross-shore temperature section collected on YD 290.8397 reveals the presence of non-homogenous cross shelf stratification. The cross-shore section of optics illustrates a strong concentration of particulate load located at 100 m. The bottom plot illustrates particles advected offshore on a 10°C isotherm.

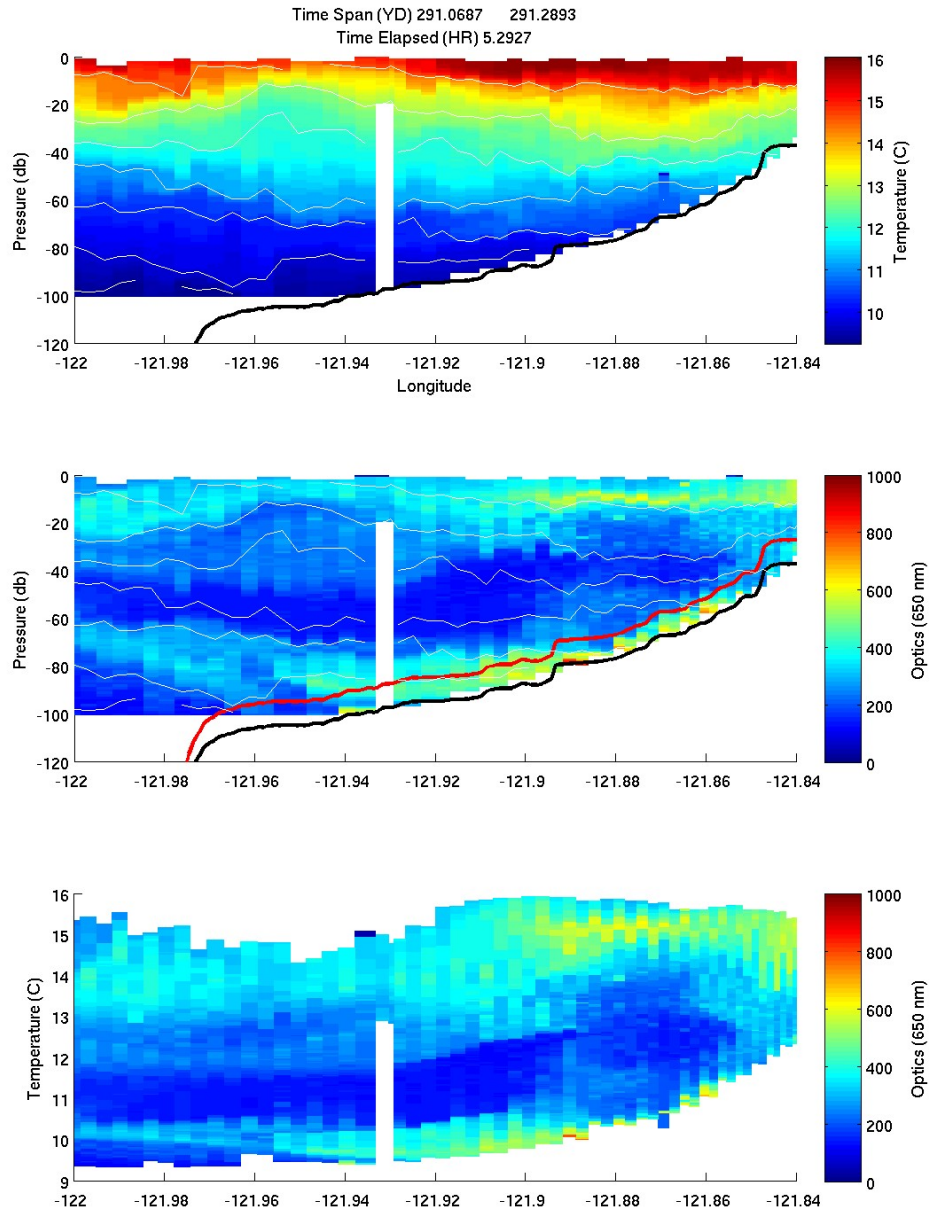


Figure 28. As in Figure 26 Tethys cross-shore temperature section collected on YD 291.0687 reveals the presence of non-homogenous cross shelf stratification. The cross-shore section of optics illustrates a strong concentration of particulate load located at 100 m. The bottom plot illustrates particles advected offshore on a 10°C isotherm.

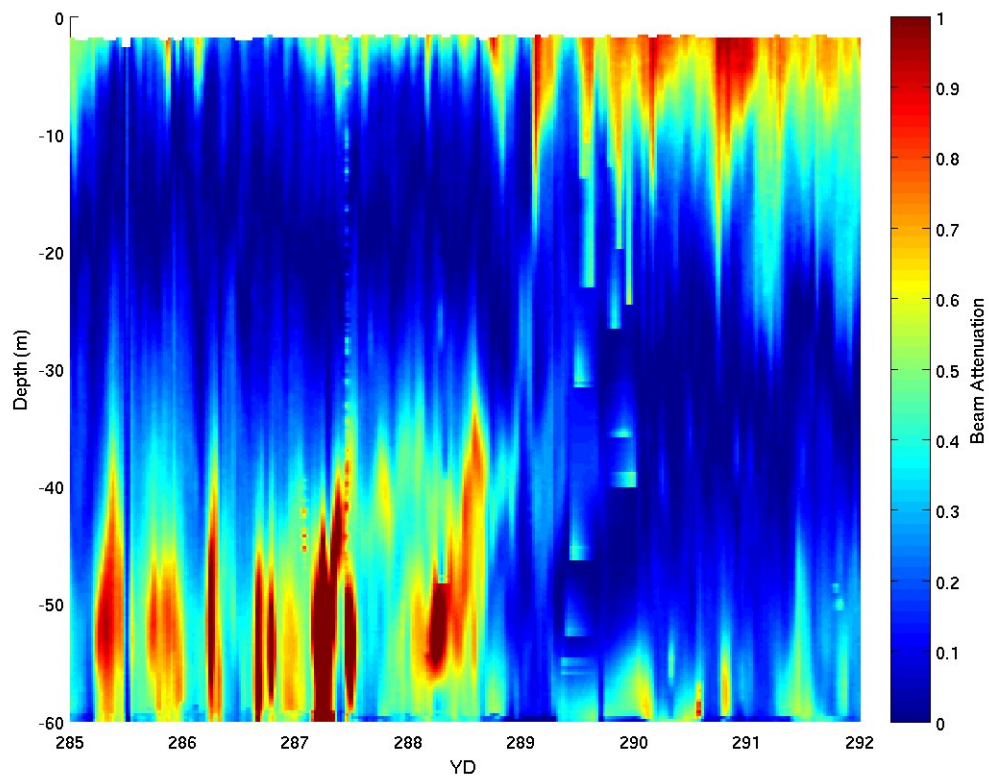


Figure 29. SeaHorse optical timeseries indicates heightened periods of density at 70 m. The enhanced signature of particulate load from YD 285 to YD 288 corresponds to the initial upwelling period when a strong shallow stratification was present near shore.

IV. DISCUSSION

A. INTERNAL TIDAL BORE EVENTS

Monterey Bay experiences strong near surface stratification during the spring and summer season approximating a two-layer system due to extended periods of upwelling. During the course of the Monterey Bay experiment a shift in wind direction occurred on YD 288 and lasted until YD 290. The raw data of both moored instruments as well as Tethys capture the impact that the shift of wind had on the stratification of the ocean. The characteristically strong near surface stratification uniformly present across the shelf during the spring and summer months undergoes a drastic change, when warmer water, typically confined to the top layers of the ocean, are forced to depths closer to the seabed (Figure 11). The weakening stratification is directly correlated to the shift in wind and the change to a downwelling environment. During the period of downwelling from YD 288 to YD 290, the density profiles revealed a significantly weakened stratification. For internal tidal bores to successfully propagate across the shelf the stratification had to be strong and laterally continuous cross-shore.

Lacking cross-shore salinity data we are unable to determine the Brunt Vaisala frequency which would provide concrete results on the stratification strength throughout both upwelling and downwelling periods in the experiment. Instead, an analysis of the Tethys cross shore temperature measurements is used to reveal the presence of a non-uniform cross shelf stratification. The high resolution cross-shore sections provided by Tethys rapid data sampling indicates that unlike the initial period of upwelling (Figure 21) when a strong stratification was uniform across the shelf, the second upwelling period illustrates a highly discontinuous stratification cross shelf (Figure 27). The stratification at depths of 100 m is significantly stronger than the stratification present at 70 m on the same YD. The Tethys cross-shelf data, corroborate with the Brunt Vaisala calculations, which determined that the water column at 70 m depth does not restratify until YD 292. Unfortunately, YD 292 also marked the end of the Tethys experiment and therefore measurements taken on this day were not available to support the moored profilers

stratification measurements. The non-uniform stratification present during the second upwelling period could be the main factor affecting the absence of a near bed particulate signature at 70 m depth.

A strong uniform near surface stratification and strong shallow buoyancy force are the optimal ocean environment for the generation and cross-shelf propagation of ITBs. These two conditions are characteristically found during periods of upwelling, and therefore during YD 285 to YD 287 the presence of suspension layers in the optical measurements is most apparent. High density sediment suspension layers are generated as a result of near-bed stress events associated with shoaling ITBs and other processes. The interaction of the bore with the sea bed creates turbulent mixing as well as heightened stress on seabed materials. These materials are then entrained in the water column forming nepheloid layers that are advected offshore on isopycnals. This suspensions and propagation offshore is apparent in the Tethys cross shore transects spanning the initial period of upwelling (Figure 21–23).

In order to further establish that a strong uniform stratification is essential for the generation of ITB and INL, the transects spanning the downwelling conditions are analyzed (Figure 24–25). The ocean stratification characteristics that were easily distinguishable during upwelling conditions are no longer present from YD 288 to YD 289. The weak stratification and buoyancy frequency do not provide a conducive environment for the generation of ITBs and the entrainment of material into the water column. It is important to note that downwelling conditions do not drastically affect the near seabed optical signature which is still present during these ocean conditions.

Transects of most interest to this discussion, however, are those taken during the second period of upwelling from YD 290-YD 291. Figures 26–29 represent Tethys transects taken upon Monterey Bay's return to upwelling conditions. A heightened particulate load is present at 100 m, as well as the presence of a nepheloid layer extending past the continental shelf. The concentration of near bed material however is confined to 100 m depth throughout the duration of the experiment and does not propagate onshore, like the previous period of upwelling. The main factor blocking the propagation of material on shore lies in the lack of uniform stratification across the shelf.

Over 100 m depth the stratification is much stronger, during initial YD, providing sufficient conditions for the generation of ITB. However, the stratification present at shallower depths lacks uniformity. This feathering out of stratification blocks the ability for the ITB to propagate on-shore and induce stress on the sea bed

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V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The results of the 2011 Monterey Bay experiment using two UAVs (Tethys and Spray glider), a SeaHorse profiler and a T-chain mooring, provide data to conclude that internal tidal bores propagated towards the shore and produced tall, sediment-laden boundary layer structures that evolved into intrusions. The energetic bores were most evident during periods of a strong shallow stratification, uniformly present across the shelf. Both the moored and mobile measurements of the water column indicate that maximum suspension occurs at 70m due to the composition of material at this depth.

As an internal tidal bore propagates on shore during uniformly strong and shallow cross shore stratification conditions, heightened particulate loads were present in the water column due to the flux of near bed stress entraining material into the water column. This particulate signature was traced through the advection of nepheloid layers offshore. The results of the 2011 Monterey Bay experiment validate previous laboratory experiments that concluded an energetic tidal bore induces stress on the seafloor and enhances friction and mixing of material resulting in a heightened particulate signature near the seabed. The largest particulate signature is present at depths near the “mud belt” due to the fluvial material found at this location.

B. RECOMMENDATIONS

The high-resolution measurements of Tethys data provided both a spatial and temporal description of an ITB’s propagation and transport of benthic material offshore in internal nepheloid layers. In order to better analyze the generation location of the ITB and its effect on the resuspension of material two entire upwelling and downwelling cycles should be captured in order to completely identify the effects that changing processes have on sediment resuspension, the generation of ITB, and the presence of internal nepheloid layers in the water column.

This experiment was the first time NPS used the Spray glider for oceanographic data. Spray’s inability to capture data on descending dives was not apparent until the end

of the experiment, when the data was extracted to be sorted into bins and profiles. In order to provide a highly resolved data set, like that of Tethys, it is essential that this problem be rectified for future experiments. Also equipping Spray with a bottom avoidance mechanism would allow the instrument to travel to depths much closer to the seabed and extract information on turbulent mixing and sediment entrainment.

C. FURTHER STUDIES

This experiment is the first part of a two phased experiment whose goal is to track the presence of ITB and the subsequent benthic exchange. The second deployment will take place in Fall 2012, and will provide a direct comparison between the evolution of ITB over the course of a year. The summer and fall months in Monterey favor upwelling conditions, and therefore provide the most scientifically compelling data.

This boundary-interior exchange study sets the groundwork for future studies that will directly focus on the effects of benthic exchange events on coastal blooms, shelf sediment budgets, and continental margin sedimentology. A growing understand of the effects that tidal bores have on the generation of nepheloid layers will ensure the optimal planning for naval missions and provide safety and security to sailors and marines as they embark on various operations at sea.

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